

Recent Results from STAR at RHIC

Nu Xu

Lawrence Berkeley National Laboratory

X. Dong, H. Huang, H.G. Ritter, A. Poskanzer, K. Schweda, P. Sorensen, A. Tai, F. Wang, Z. Xu



Outline

- **Introduction**
- **Energy loss - QCD at work**
- **Charm production**
- **Bulk properties - ∂P_{QCD}**
- **Summary and Outlook**



Other STAR Physics Topics

- 1) Correlation and fluctuation
- 2) Ultra-peripheral collision
- 3) Resonance
- 4) Spin
- 5) Pentaquark search

<http://www.star.bnl.gov/STAR/>



//talk/2004/11UCSC/nxu_ucsc_11Nov04//

Study of Nuclear Collisions Like...

P.C. Sereno *et al.* **Science**, Nov. 13, 1298(1998).

(Spinosaurid)





Physics Goals at RHIC

Identify and study the properties of matter with partonic degrees of freedom.

Penetrating probes

- direct photons, leptons
- “jets” and **heavy flavor**
- correlations

jets

- observed high p_T hadrons (at RHIC, $p_{T(\min)} > 3$ GeV/c)

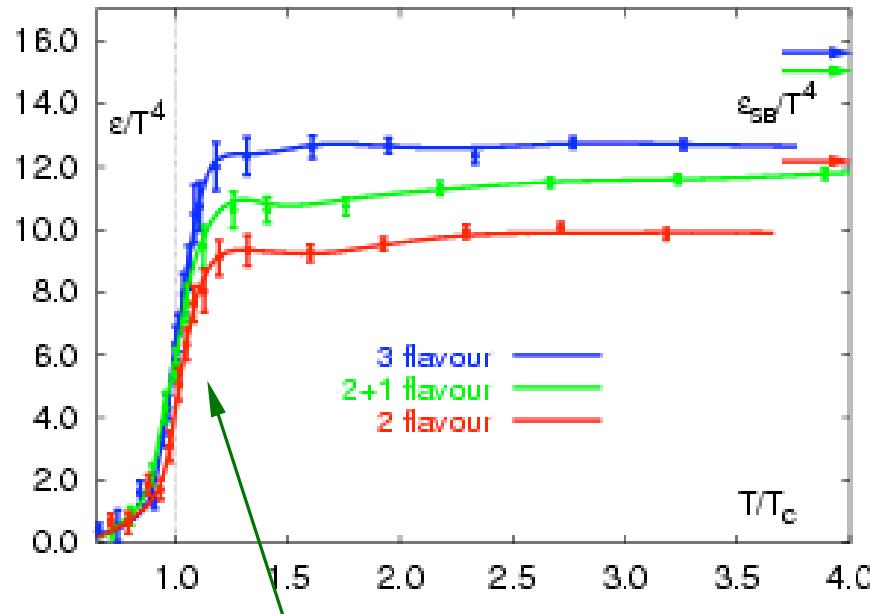
collectivity - collective motion of observed hadrons, not necessarily reached thermalization.

Bulk probes

- spectra, v_1 , v_2 ...
- partonic collectivity
- fluctuations



QCD on Lattice



Lattice calculations predict
 $T_c \sim 170$ MeV

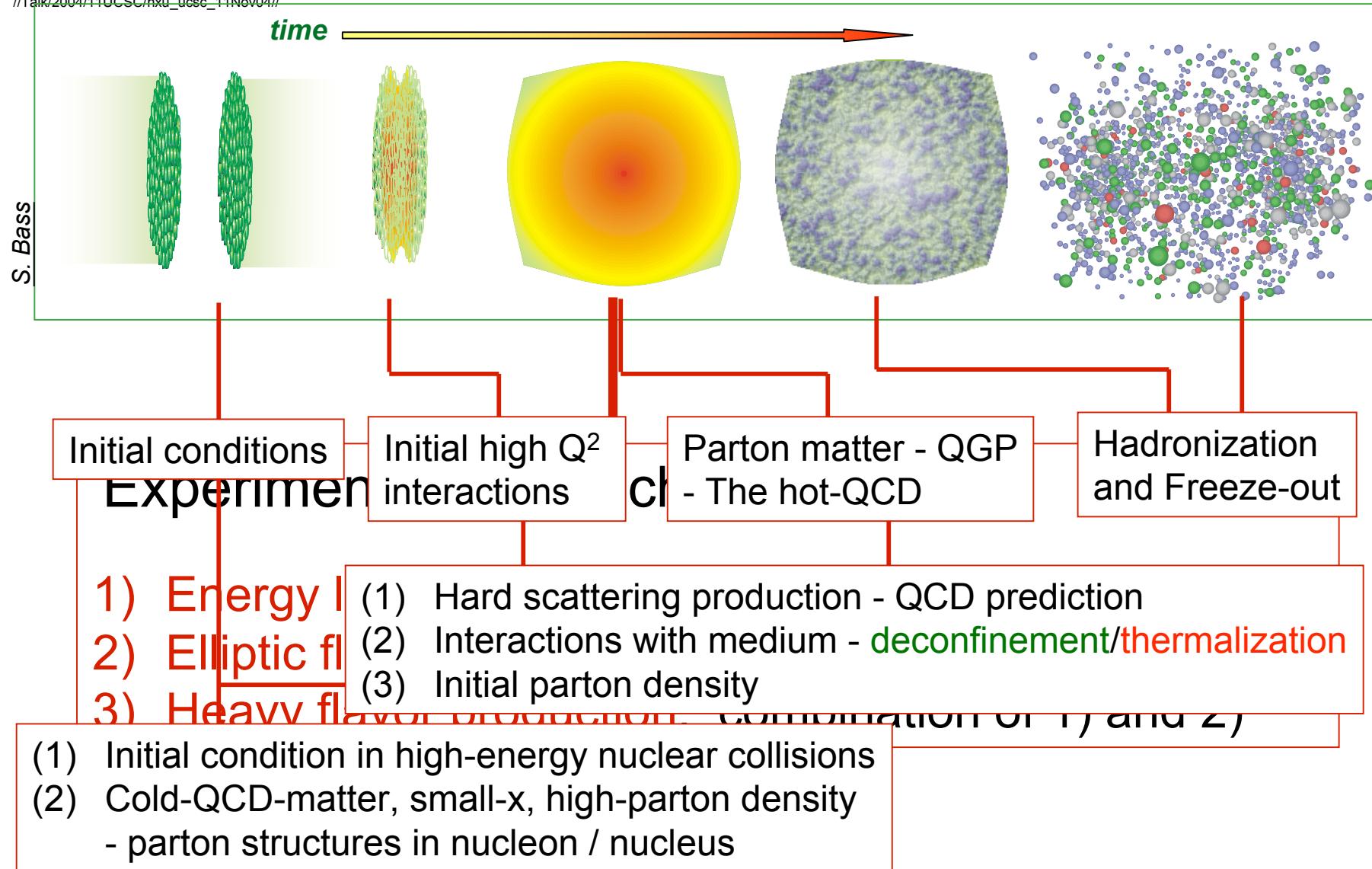
- 1) Large increase in \square
a fast cross cover !
- 2) Does not reach ideal,
non-interaction S. Boltzmann
limit !
 - \square many body interactions
 - \square Collective modes
 - \square Quasi-particles are necessary
- 3) $T_c \sim 170$ MeV robust!

Z. Fodor et al, *JHEP* 0203:014(02)
Z. Fodor et al, *hep-lat/0204001*
C.R. Allton et al, *hep-lat/0204010*
F. Karsch, *Nucl. Phys. A698*, 199c(02).



High-energy Nuclear Collisions

//talk/2004/11UCSC/nxu_ucsc_11Nov04//





High-energy Nuclear Collisions

Initial Condition

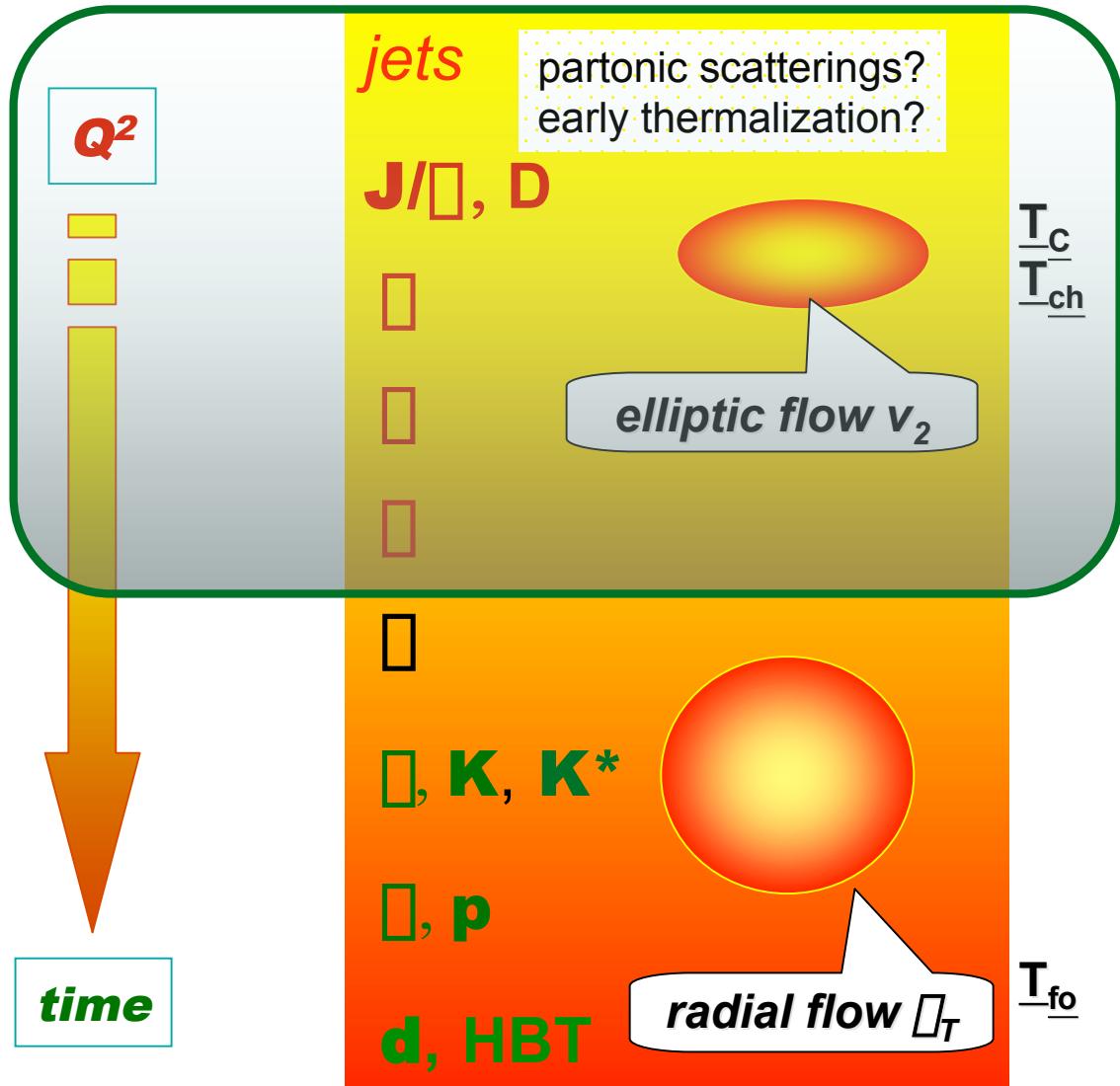
- initial scatterings
- baryon transfer
- E_T production
- parton dof

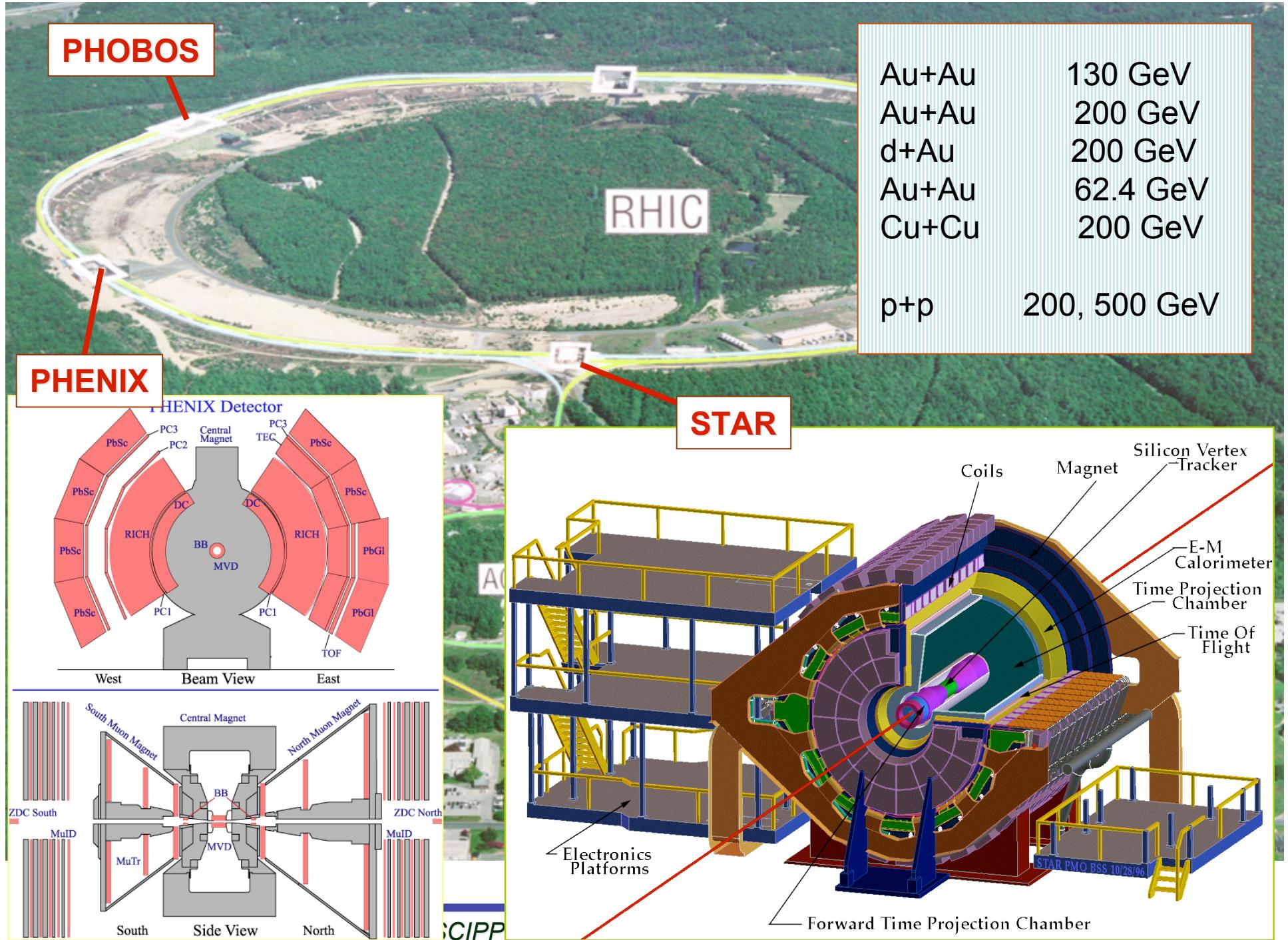
System Evolves

- parton interaction
- parton/hadron expansion

Bulk Freeze-out

- hadron dof
- interactions stop







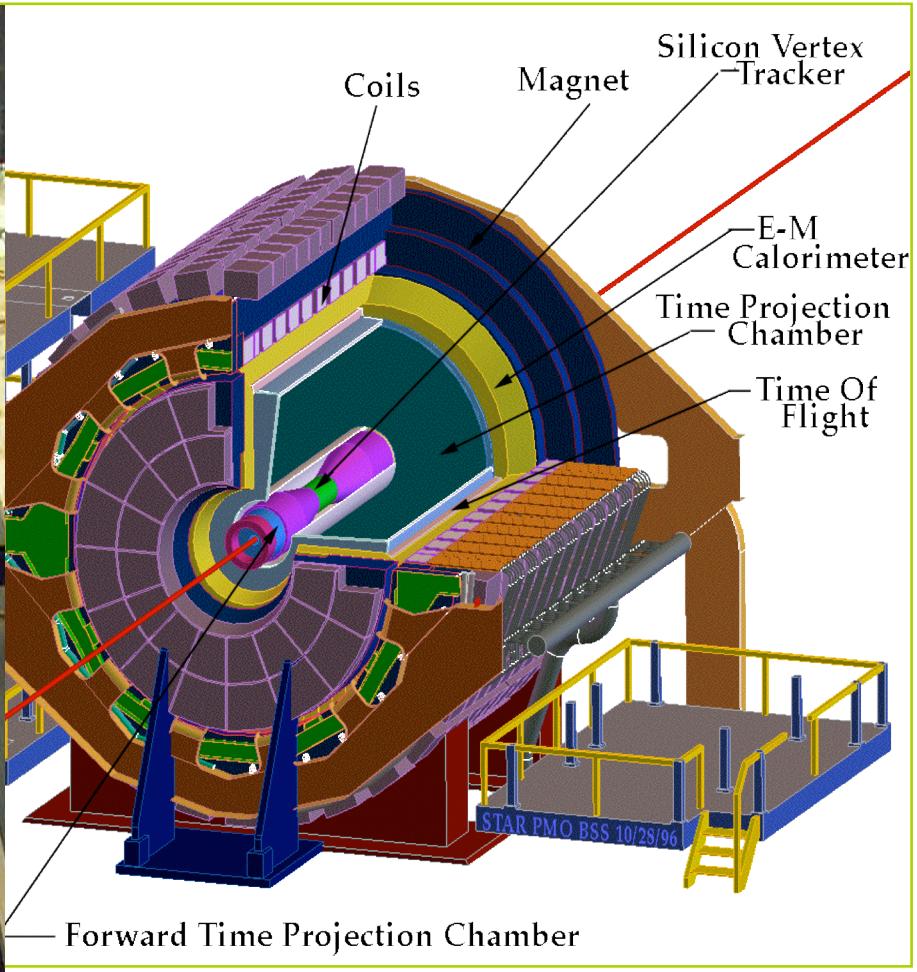
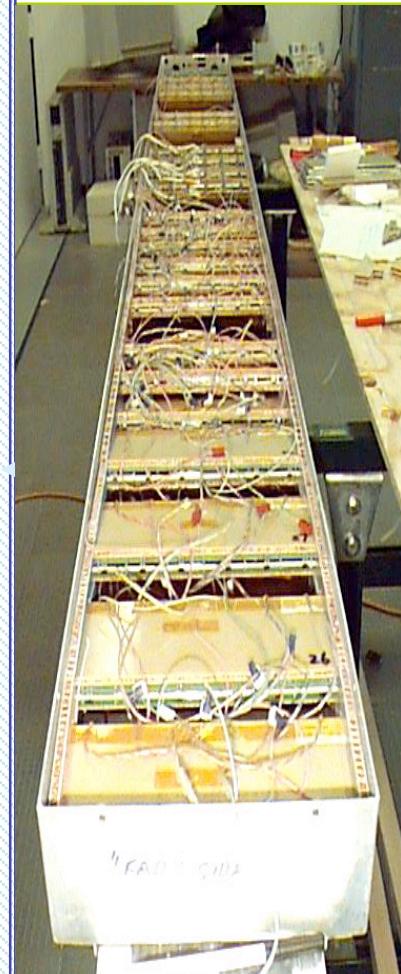
/Talk/2004/11/ICSC/avu_ncsc_11Nov04/

STAR: TPC & MRPC-TOF

A new technology -

Multi-gap Resistive Plate Chamber (MRPC), adopted from CERN-Alice

- A prototype detector of time-of-flight (**TOFr**) was installed in Run3
- One tray: ~ 0.3% of TPC coverage
- Intrinsic timing resolution: ~ 85 ps
- pion/kaon ID:**
 $p_T \sim 1.7 \text{ GeV}/c$
- proton ID:**
 $p_T \sim 3 \text{ GeV}/c$



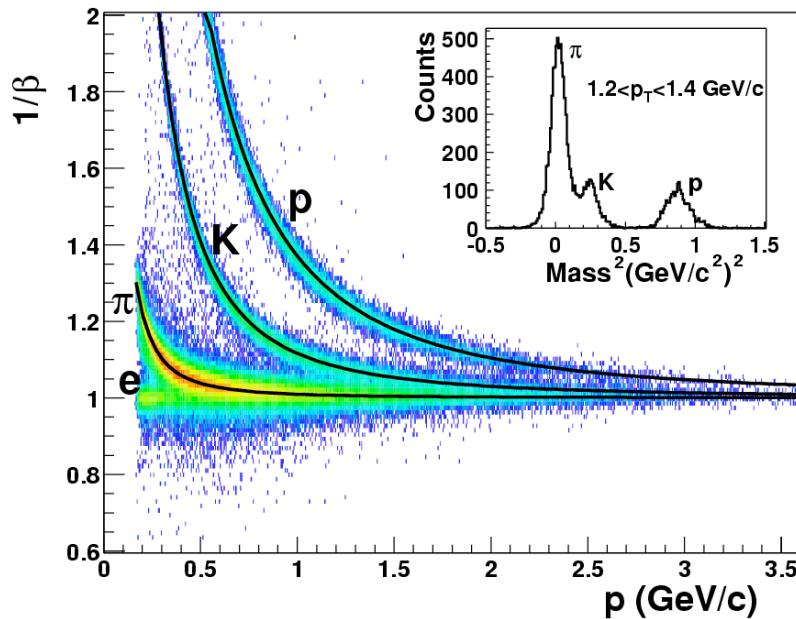
TPC dE/dx PID:

pion/kaon: $p_T \sim 0.6 \text{ GeV}/c$; proton $p_T \sim 1.2 \text{ GeV}/c$

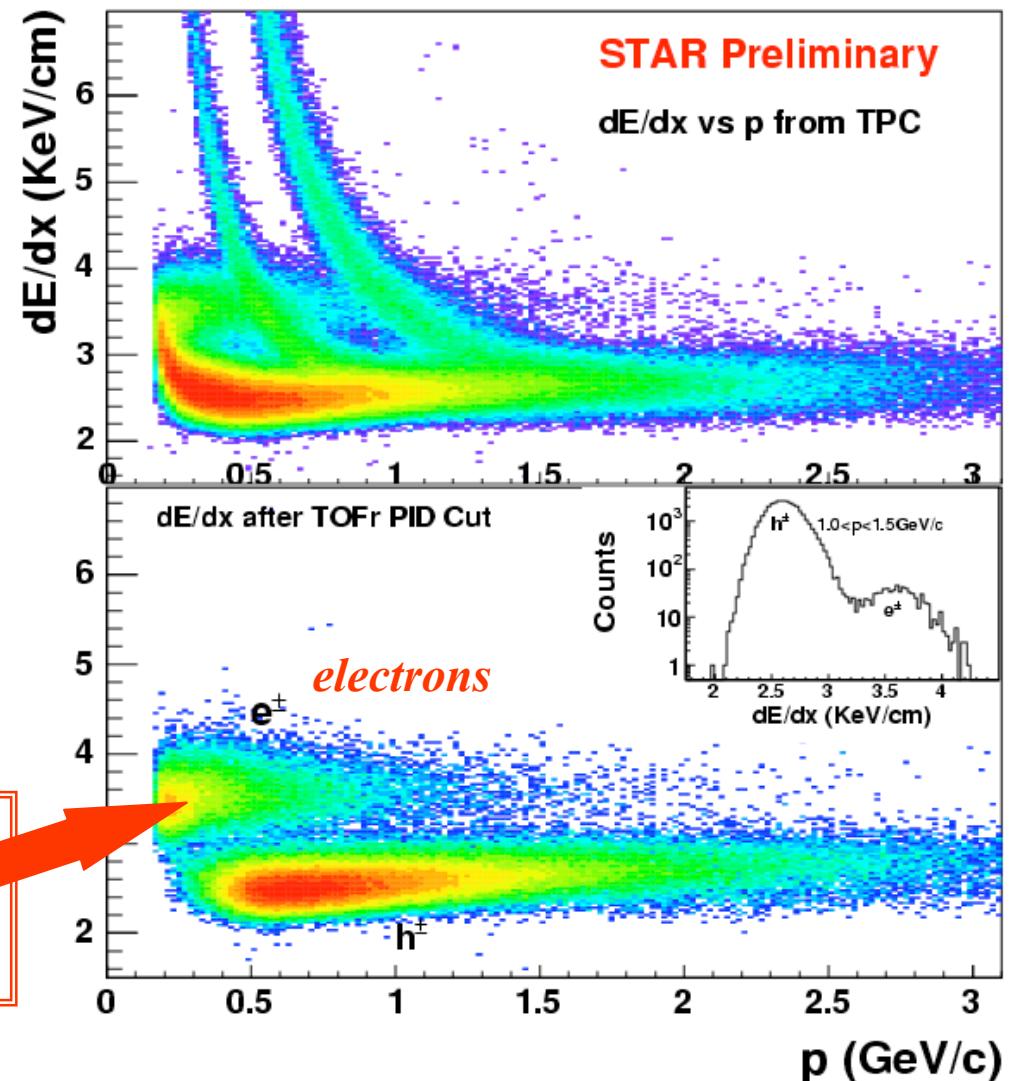


//talk/2004/11UCSC/nxu_ucsc_11Nov04//

STAR TOFr PID



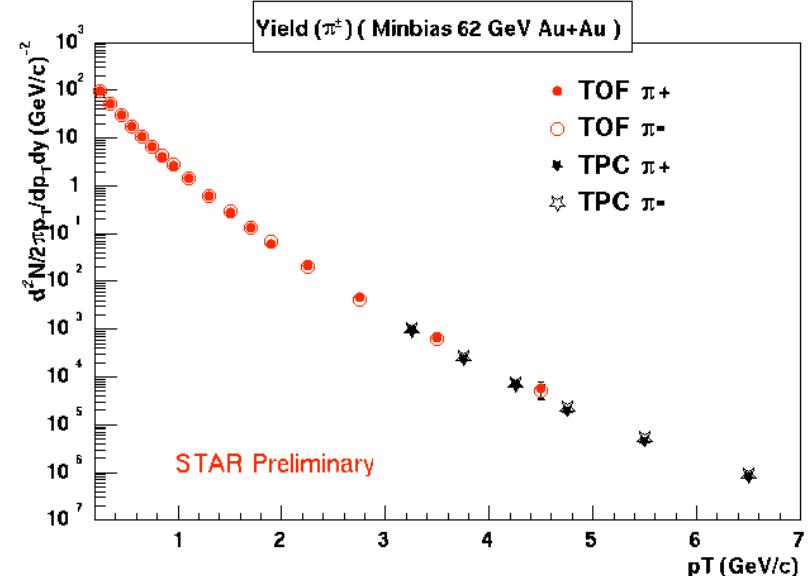
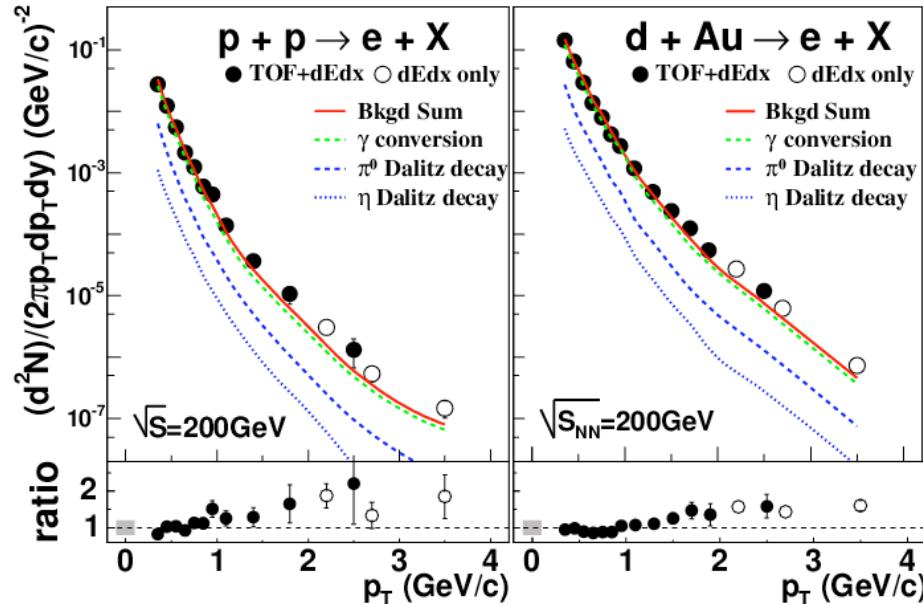
Hadron identification:
STAR Collaboration, [nucl-ex/0309012](https://arxiv.org/abs/nucl-ex/0309012)



Electron identification:
TOFr $|1/\beta - 1| < 0.03$
TPC dE/dx electrons!!!

Electron, pion spectra

STAR Preliminary



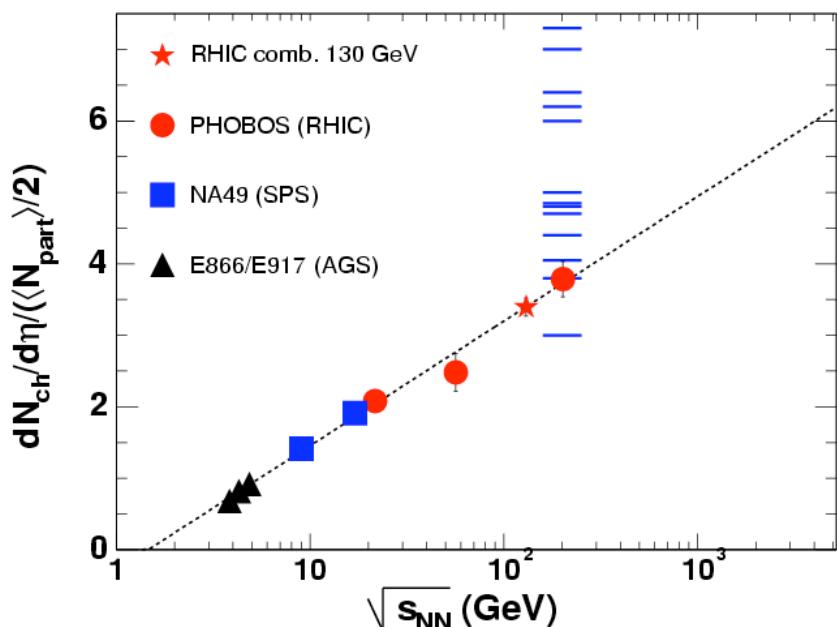
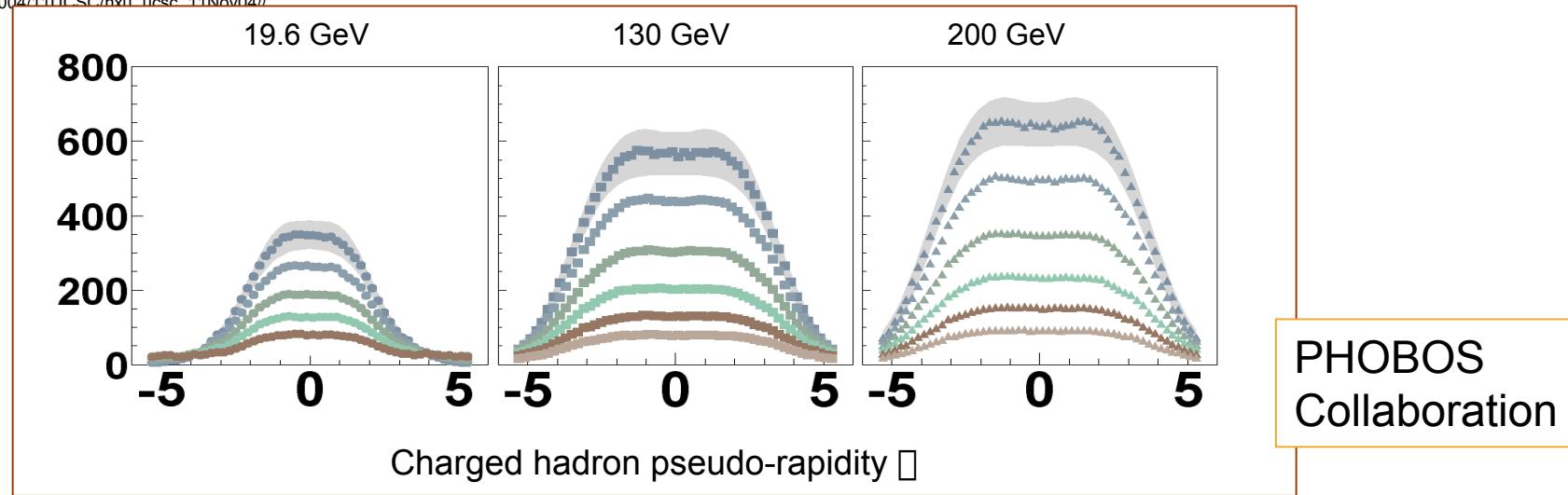
- 1) An increasing excess found at higher p_T region, $p_T > 1.0 \text{ GeV}/c$,
→ Expected contribution of semi-leptonic decays from heavy flavor hadrons
- 2) Pion identification up to $p_T \sim 7 \text{ GeV}/c$

STAR: [nucl-ex/0407006](#)



//talk/2004/11/LCSC/hvli/ucsc_11Nov04//

Global: Charge hadron density



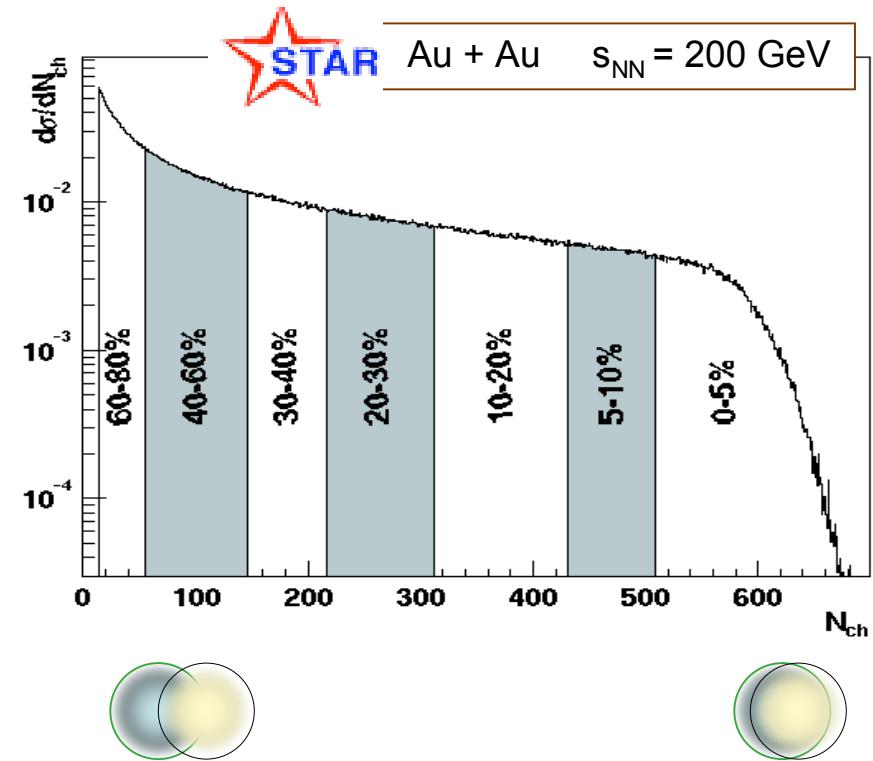
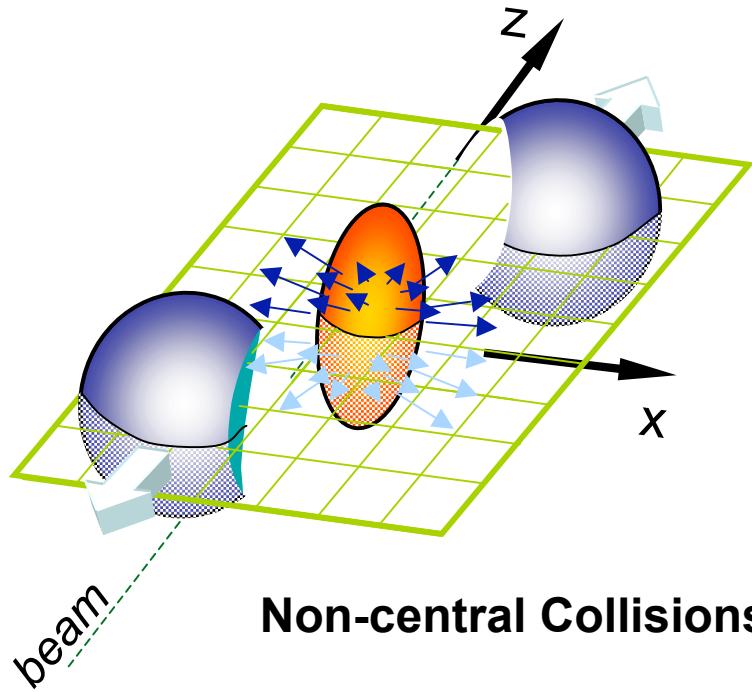
- 1) High number of N_{ch} indicates initial high density;
- 2) Mid-y, $N_{ch} \propto N_{part} \Rightarrow$ nuclear collisions are not incoherent;

Important for high density and thermalization.

PRL 85, 3100 (00); 91, 052303 (03); 88, 22302 (02), 91, 052303 (03)



Collision Geometry



Number of participants: number of incoming nucleons in the overlap region

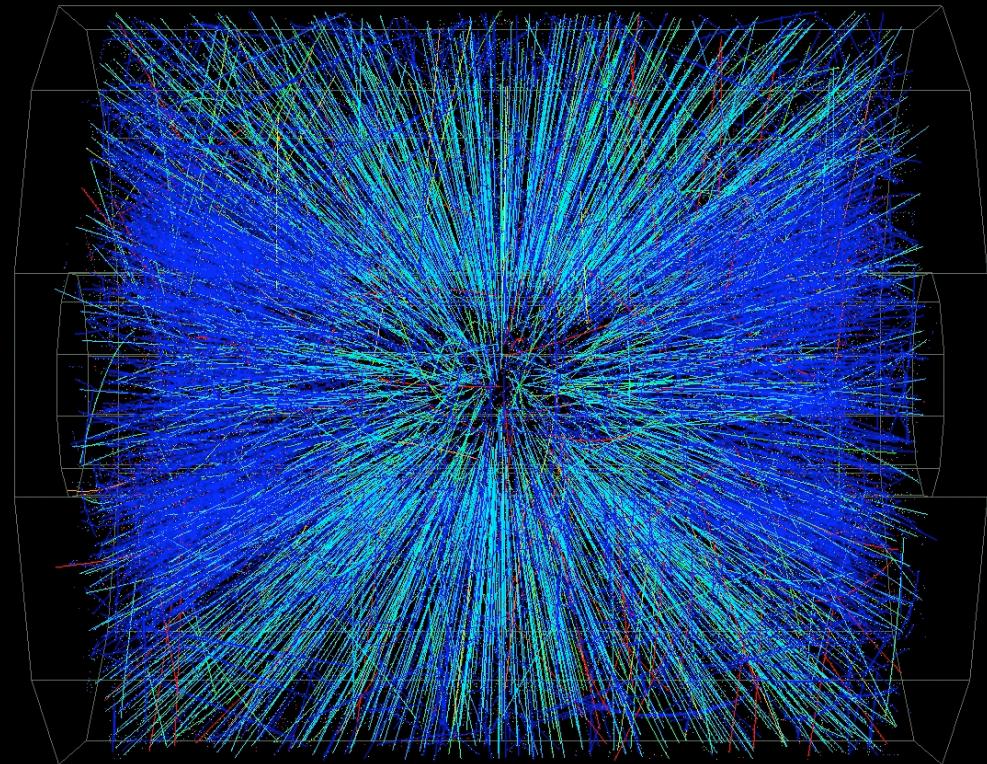
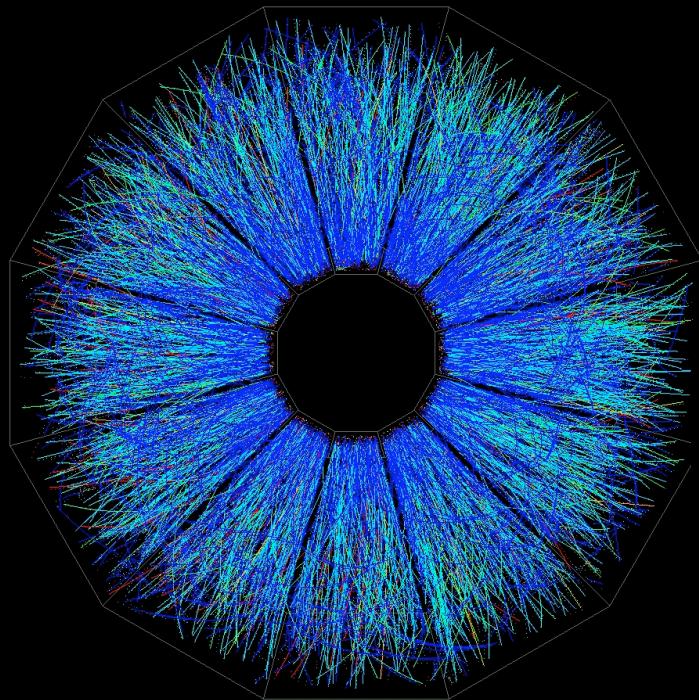
Number of binary collisions: number of inelastic nucleon-nucleon collisions

Charged particle multiplicity collision centrality

Reaction plane: x-z plane

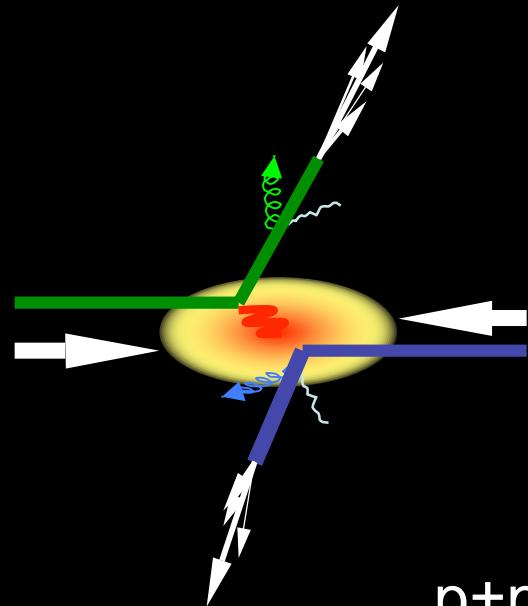
Au + Au Collisions at RHIC

Central Event

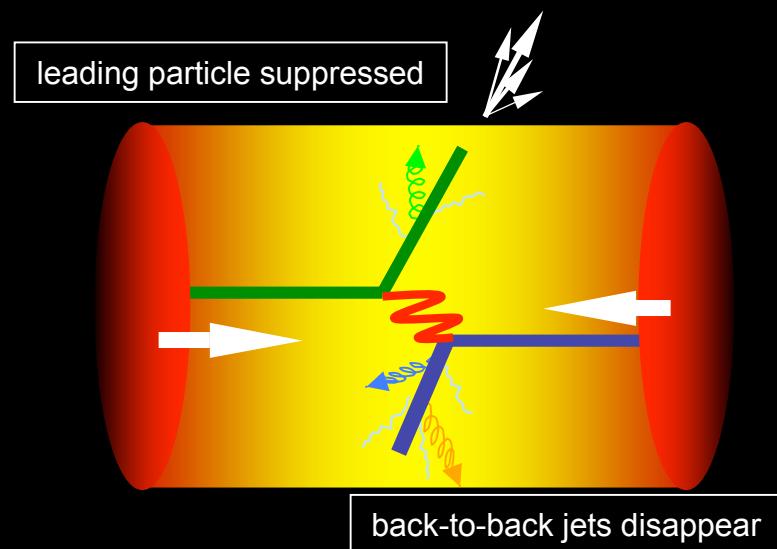


(real-time Level 3)

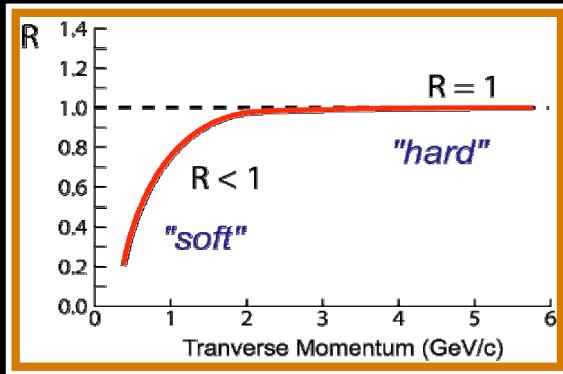
Energy Loss in A+A Collisions



$p+p$



$Au + Au$



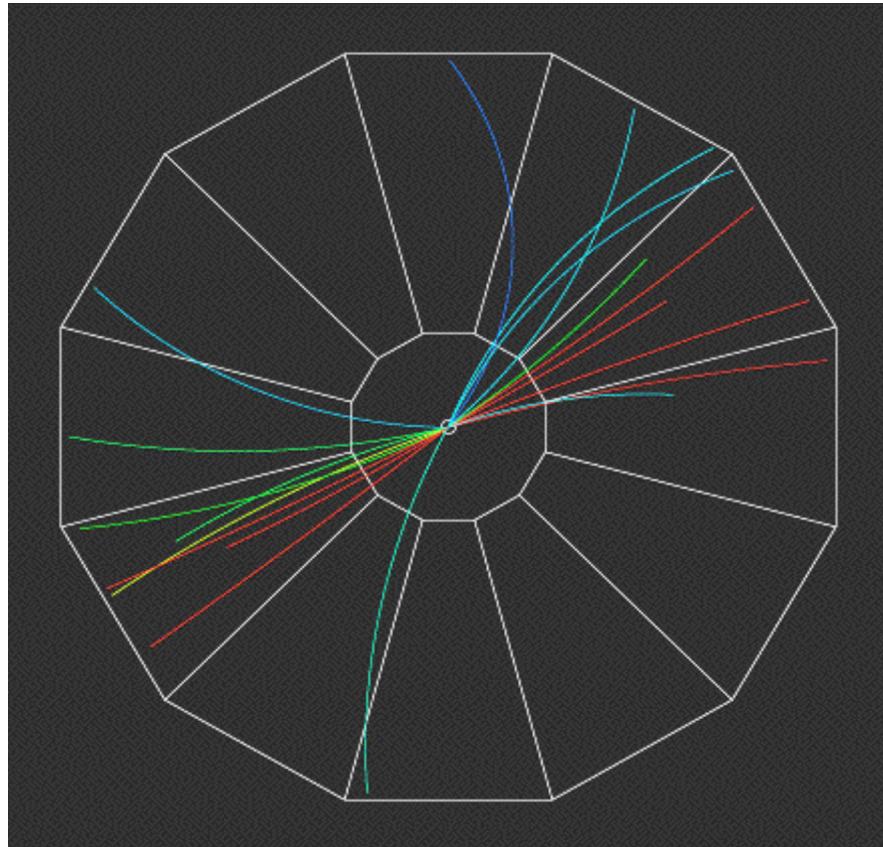
Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2 N^{AA} / dp_T d\Omega}{d^2 \Omega^{NN} / dp_T d\Omega}$$

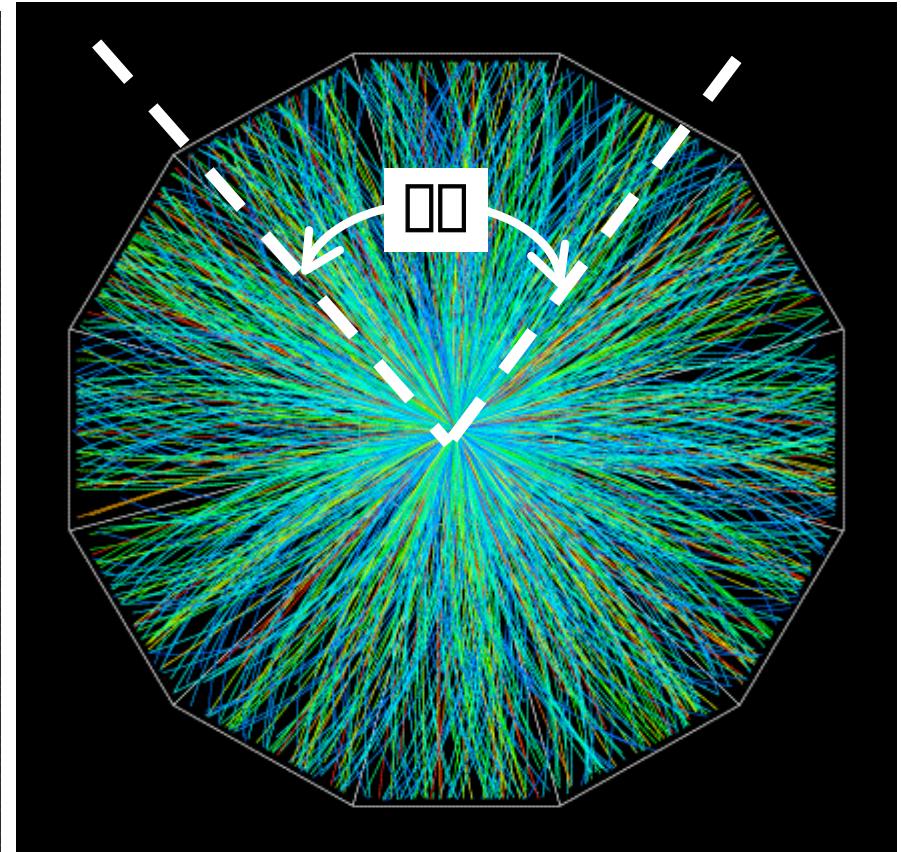


//talk/2004/11UCSC/nxu_ucsc_11Nov04//

'Jets' Observation at RHIC



p+p collisions at RHIC
Jet like events observed

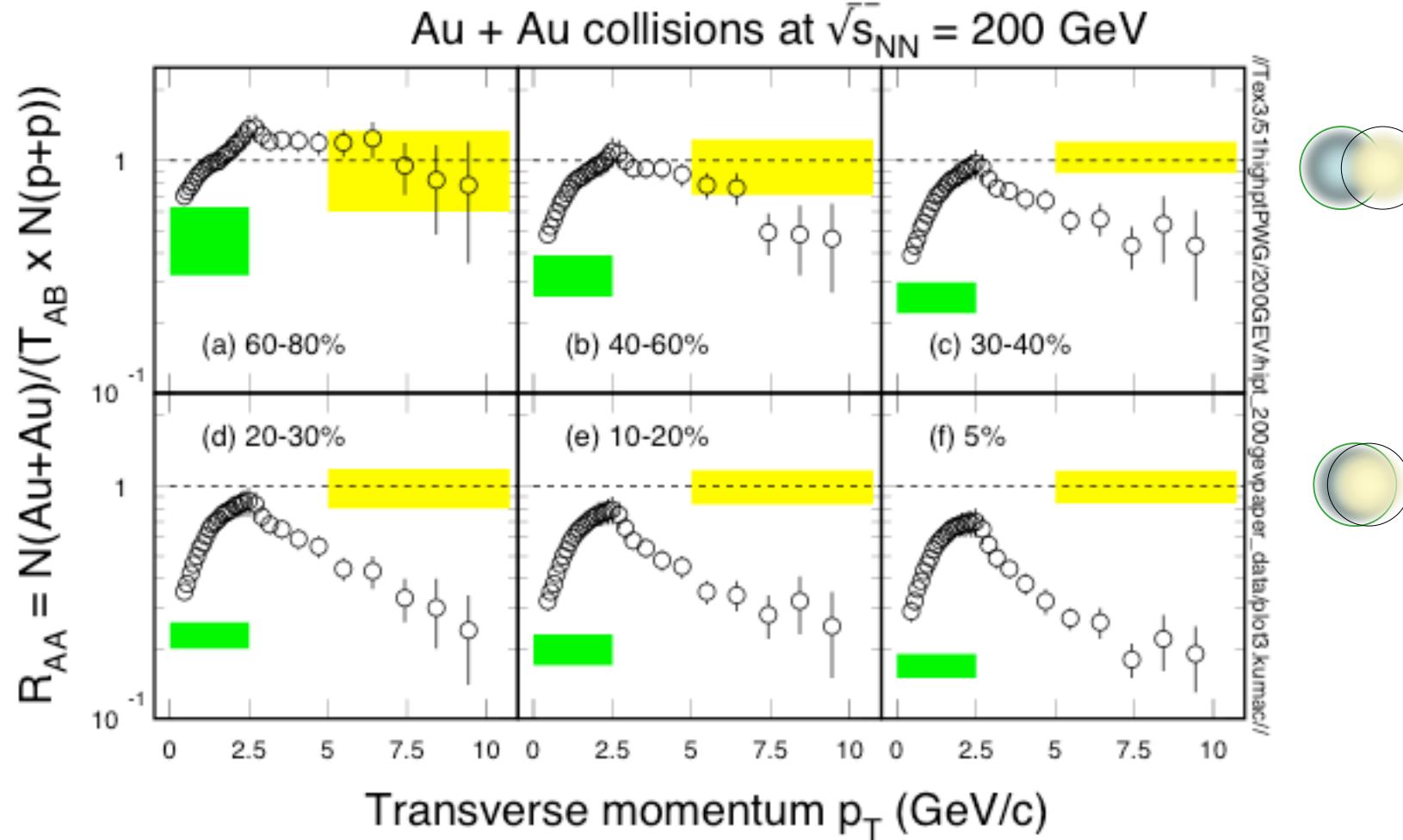


Au+Au collisions at RHIC
Jets effects?



//Talk/2004/11/ICSC/pxv11.psc 11Nov04//

Hadron Suppression at RHIC



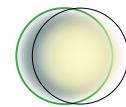
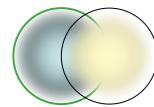
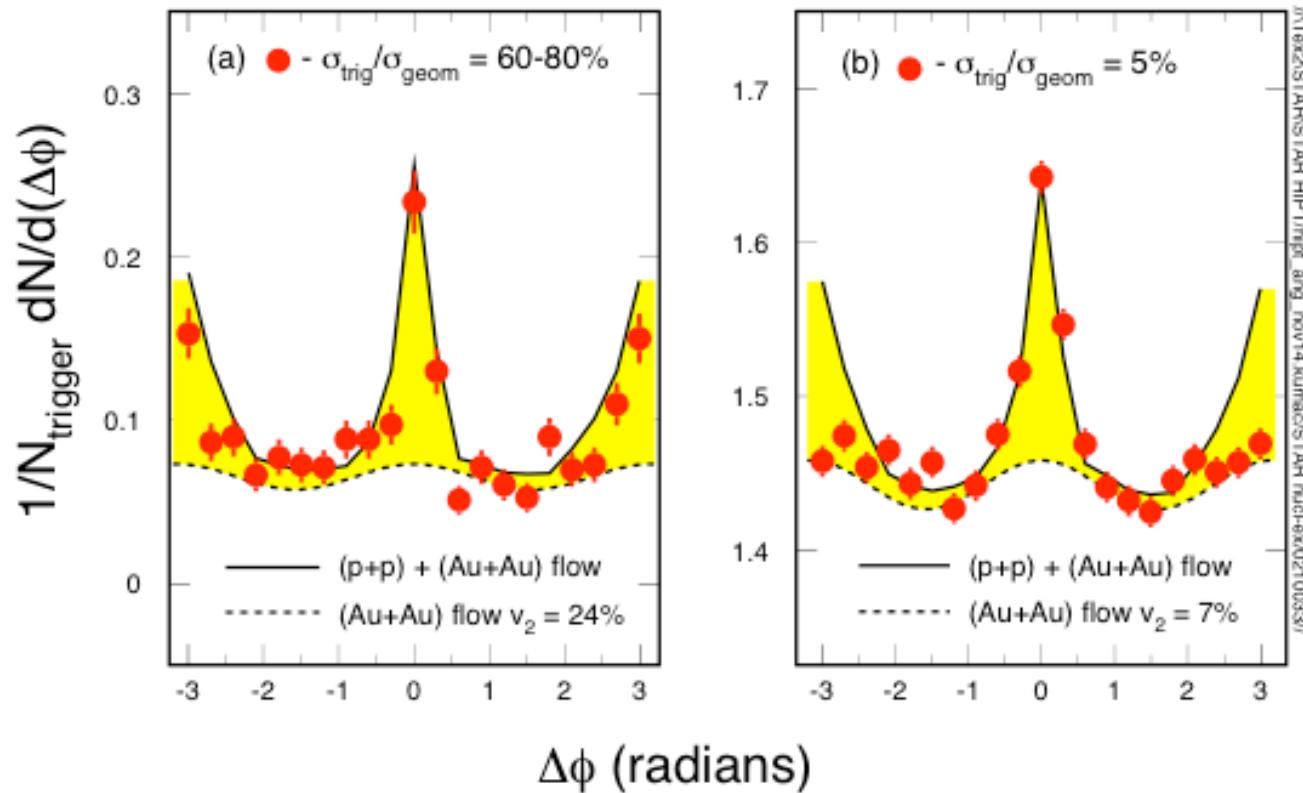
Hadron suppression in more central Au+Au collisions!



//talk/2004/11UCSC/nxu_ucsc_11Nov04//

Jet angular correlations

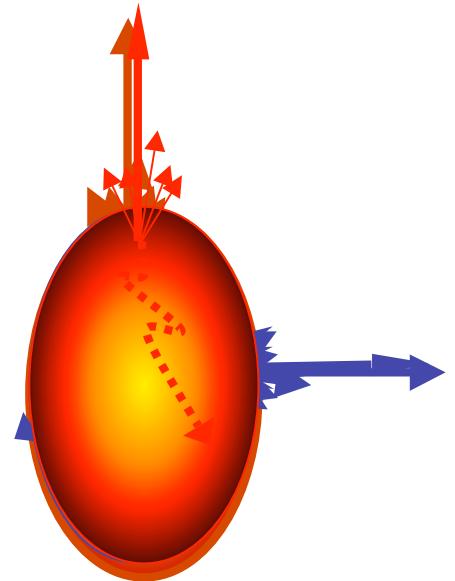
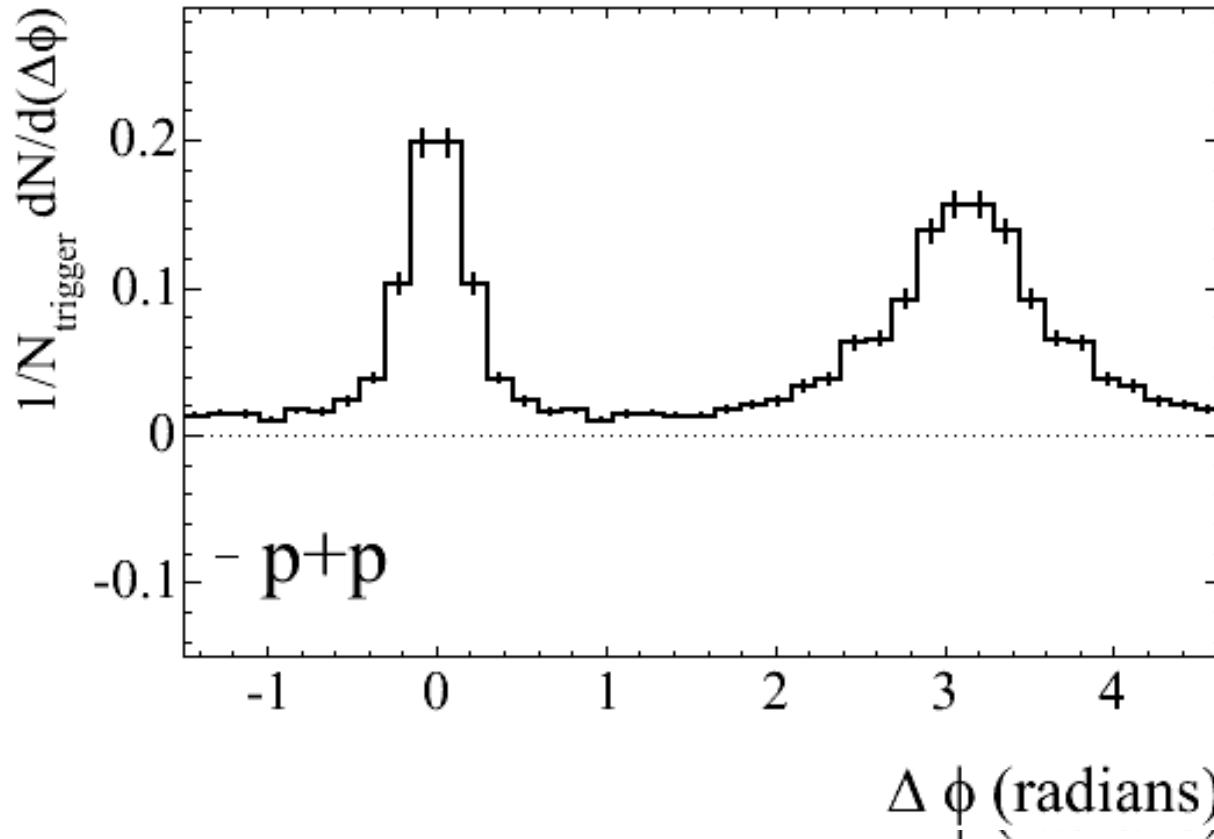
$^{197}\text{Au} + ^{197}\text{Au}$ at RHIC ($\sqrt{s_{\text{NN}}} = 200 \text{ GeV}$)





Azimuthal Angular Dependence

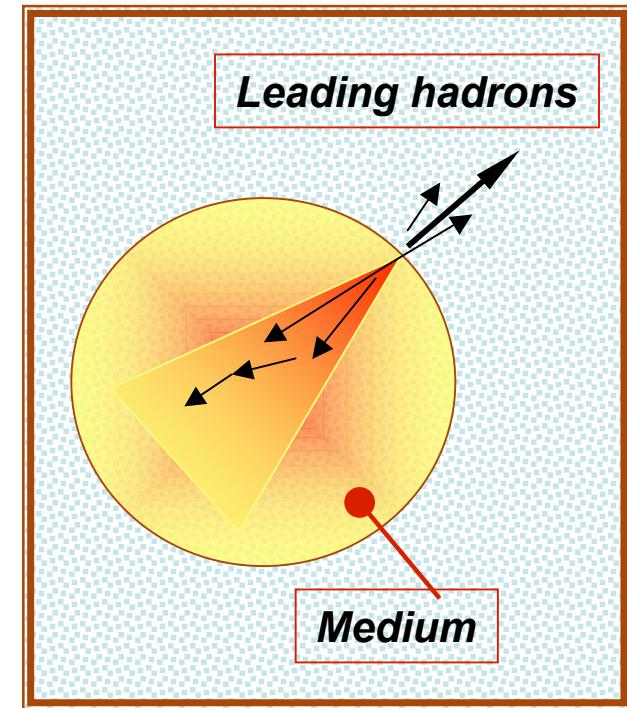
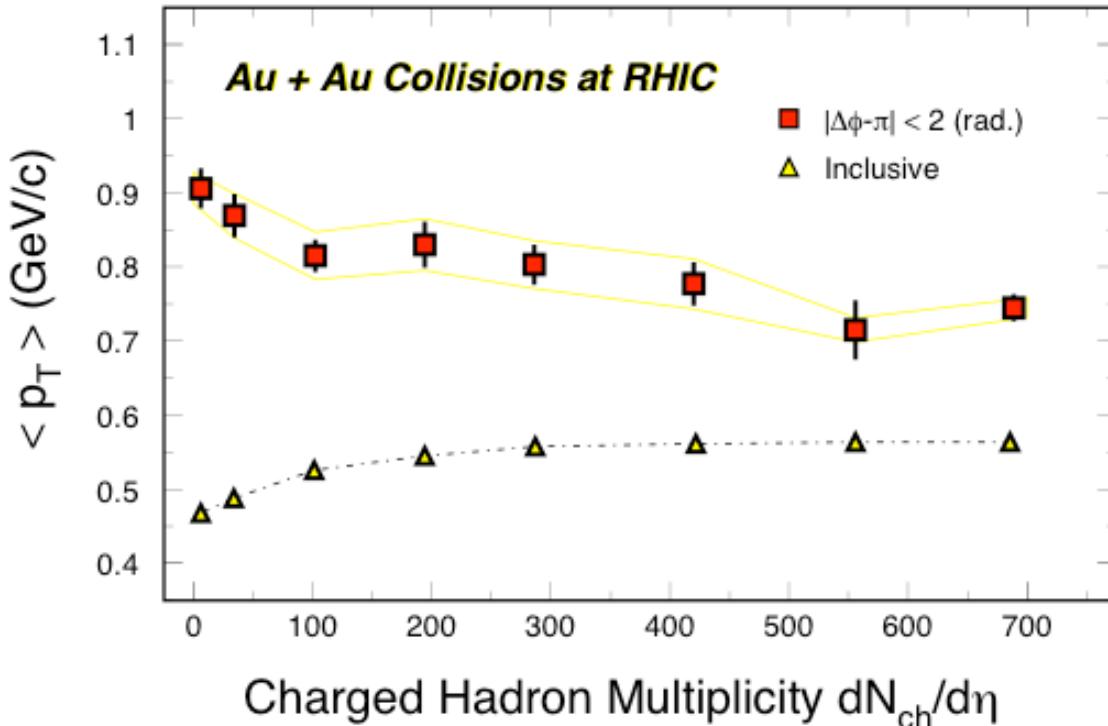
//Talk/2004/11/ICSC/nucl-nuc 11Nov04//



- Away-side suppression: larger for out-of-plane than in-plane!
- The energy loss depends on the distance traveled through the medium!
- Geometry of the dense medium imprints itself on correlations!



Energy Loss and Equilibrium



In Au +Au collision at RHIC:

- Suppression at the intermediate p_T region - energy loss
- The energy loss leads to progressive equilibrium in Au+Au collisions

STAR: *nucl-ex/0404010*



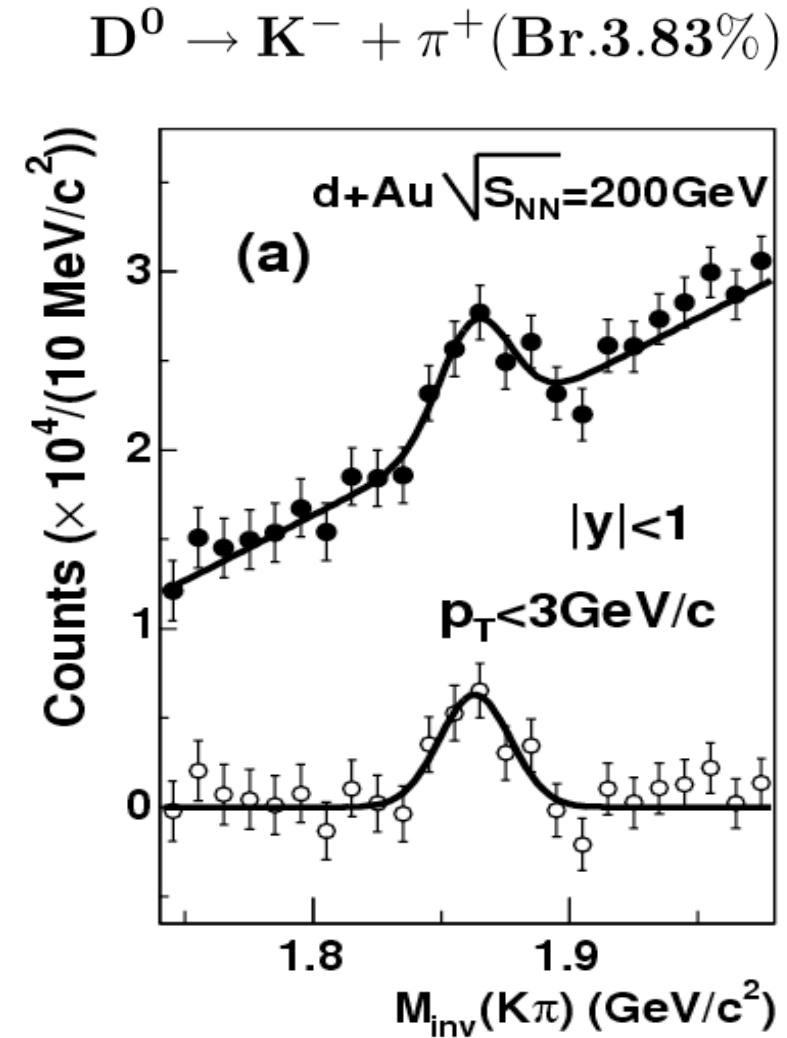
Direct reconstruction of D⁰

- 1) Heavy flavor production sensitive to medium effect - energy loss and collective effect;
- 2) Large cross section - parton thermalization and J/ψ
- 3) Better pQCD predictions(?)

First direct open charm reconstruction at RHIC!

Event mixing method:

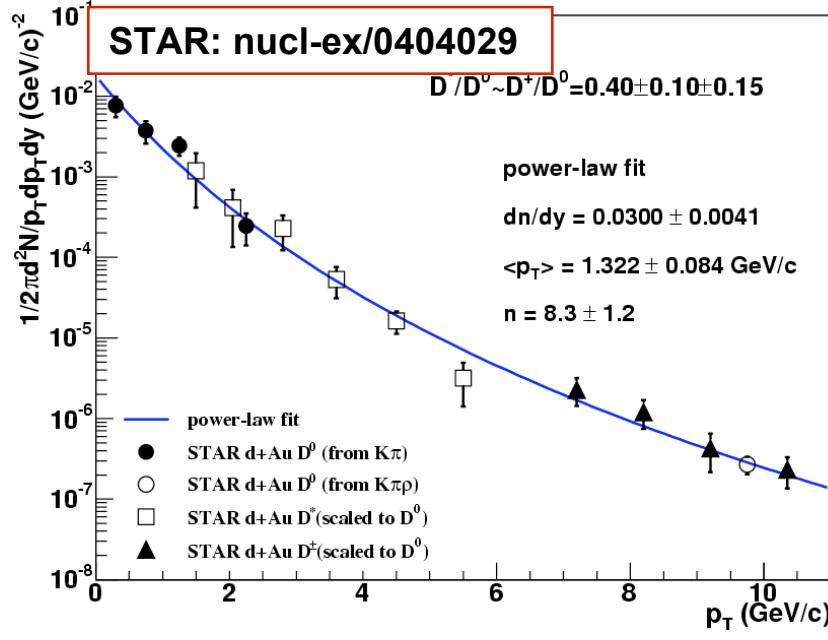
C. Adler et al., *Phys. Rev. C66*, 061901(R)(2002)
H. Zhang, *J. Phys. G30*, S577(2004)



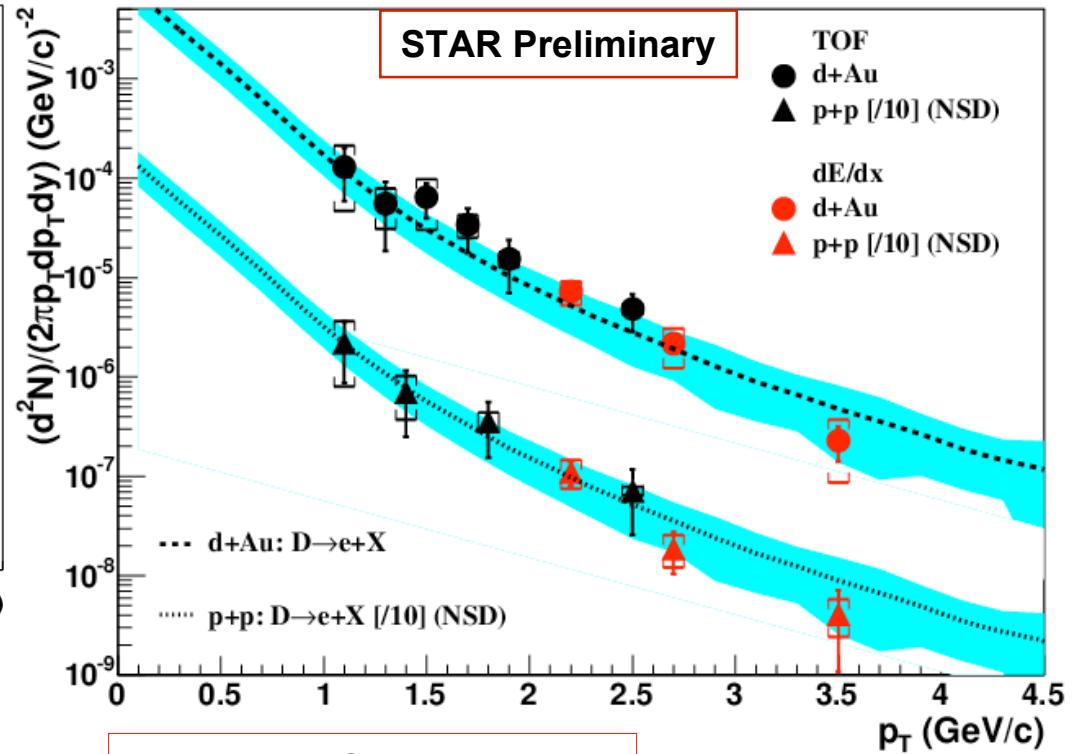


//talk/2004/11UCSC/nxu_ucsc_11Nov04//

Consistent in D measurements



Directly reconstructed D mesons

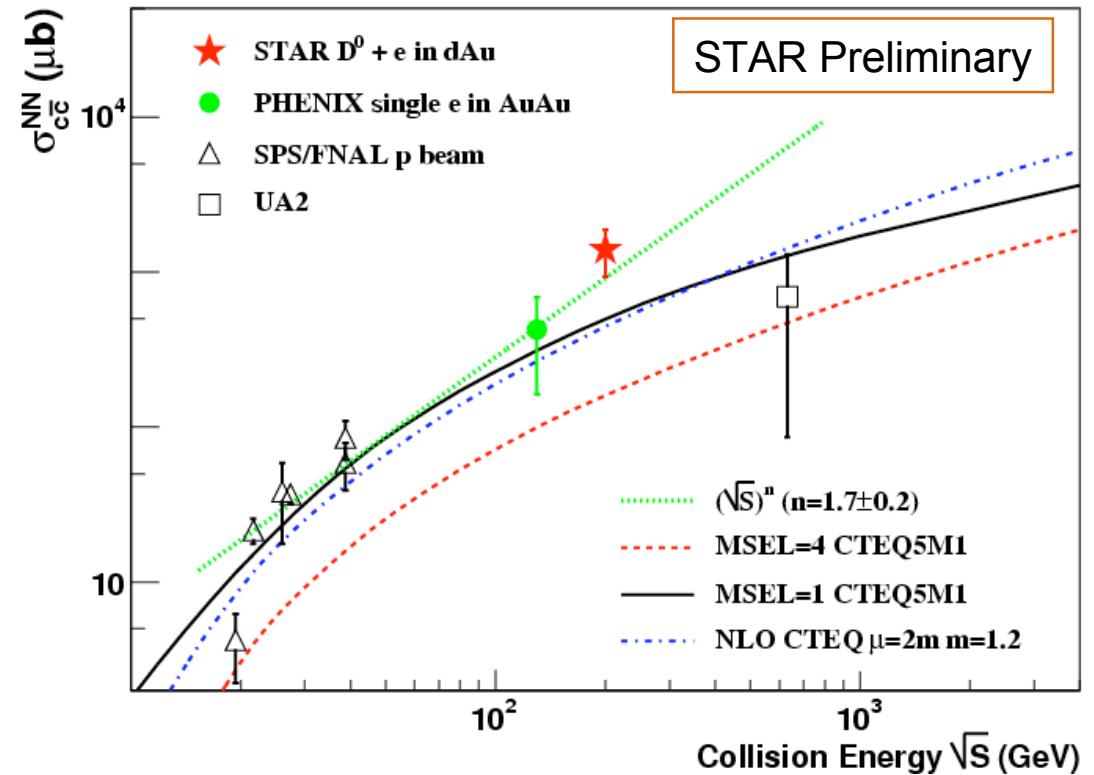


Electrons from D decay

D and electron spectra are consistent!

Charm production cross-section

- 1) NLO pQCD calculations under-predict the ccbar production cross section at RHIC
- 2) Power law for ccbar production cross section from SPS to RHIC:
 $n \sim 2$
(n~0.5 for charged hadrons)
- 3) Large uncertainties in total cross section due to rapidity width, model dependent(?).





Charm production at RHIC

- 1) Open charm yields measured in both 200GeV p+p and d+Au collisions. No evidence of deviation from binary collision scaling in d+Au collisions

$$\bar{\Lambda}_{c\bar{c}}^{\text{total}} = 700 \pm 1200 (\text{fb})$$

- 2) Perturbative calculations under predicted both yields and spectrum shape. Hadronization process not under control
 - 1) Study open charm v_2 and J/ψ yields to address thermalization issues at RHIC.



Pressure, Flow, ...

$$\boxed{dU} = dU + pdV$$

\square - entropy; p – pressure; U – energy; V – volume
 $\square = k_B T$, thermal energy per dof

In high-energy nuclear collisions, *interaction* among constituents and *density distribution* will lead to:

pressure gradient* \square *collective flow

- \square number of degrees of freedom (dof)
- \square Equation of State (EOS)
- \square No thermalization needed – pressure gradient only depends on the ***density gradient and interactions***.
- \square Space-time-momentum correlations!



Transverse Flow Observables

$$\frac{dN}{p_t dp_t dy d\Omega} = \frac{1}{2\Omega} \frac{dN}{p_t dp_t dy} \left[1 + \sum_{i=1}^{\Omega} 2v_i \cos(i\Omega) \right]$$
$$p_t = \sqrt{p_x^2 + p_y^2}, \quad m_t = \sqrt{p_t^2 + m^2}$$

As a function of particle mass:

- Directed flow (v_1) – early
- Elliptic flow (v_2) – early
- Radial flow – integrated over whole evolution

Note on collectivity:

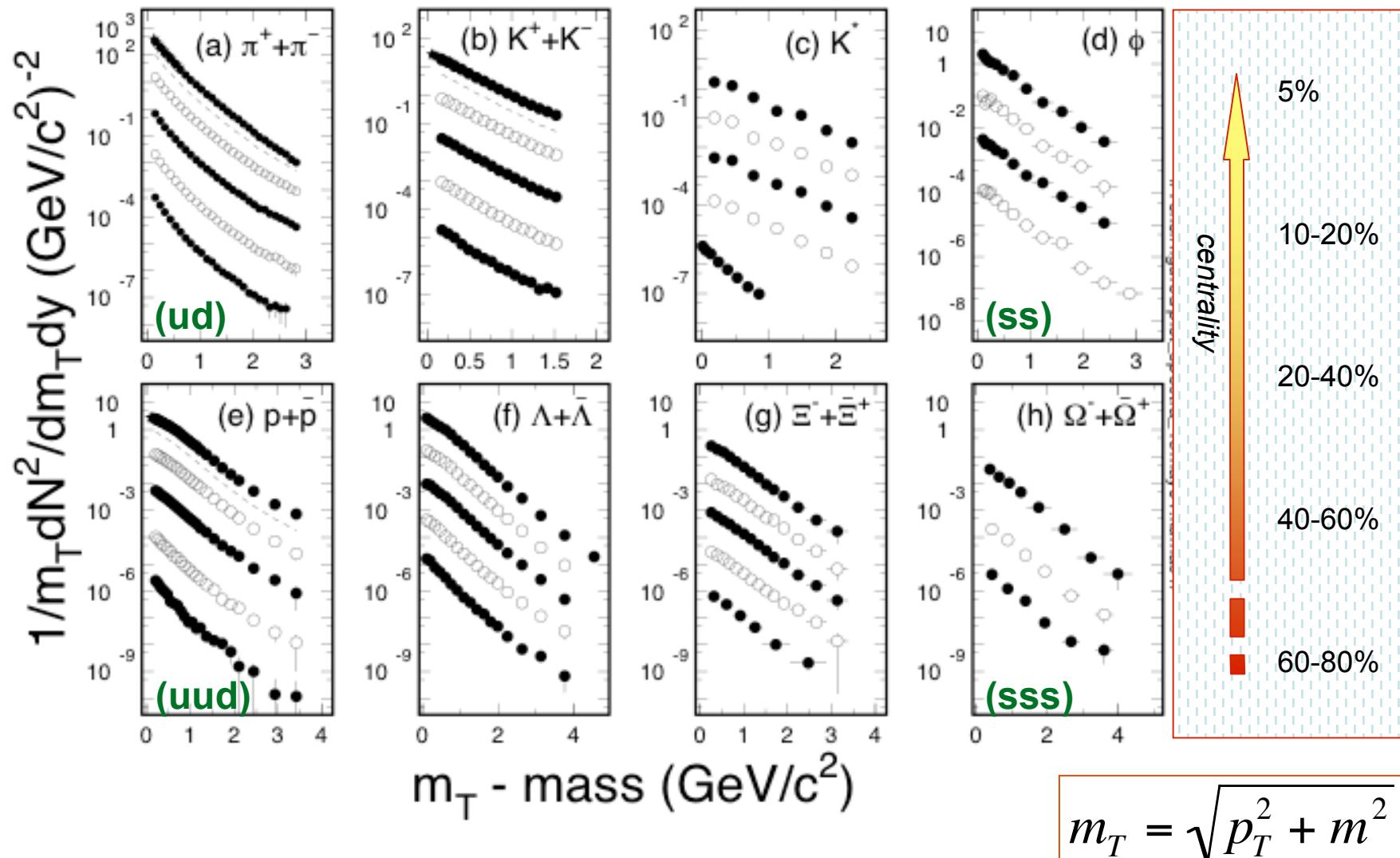
- 1) Effect of collectivity is accumulative – final effect is the sum of all processes.
- 2) Thermalization is not needed to develop collectivity - pressure gradient depends on **density gradient** and **interactions**.



//talk/2004/11UCSC/nxu_ucsc_11Nov04//

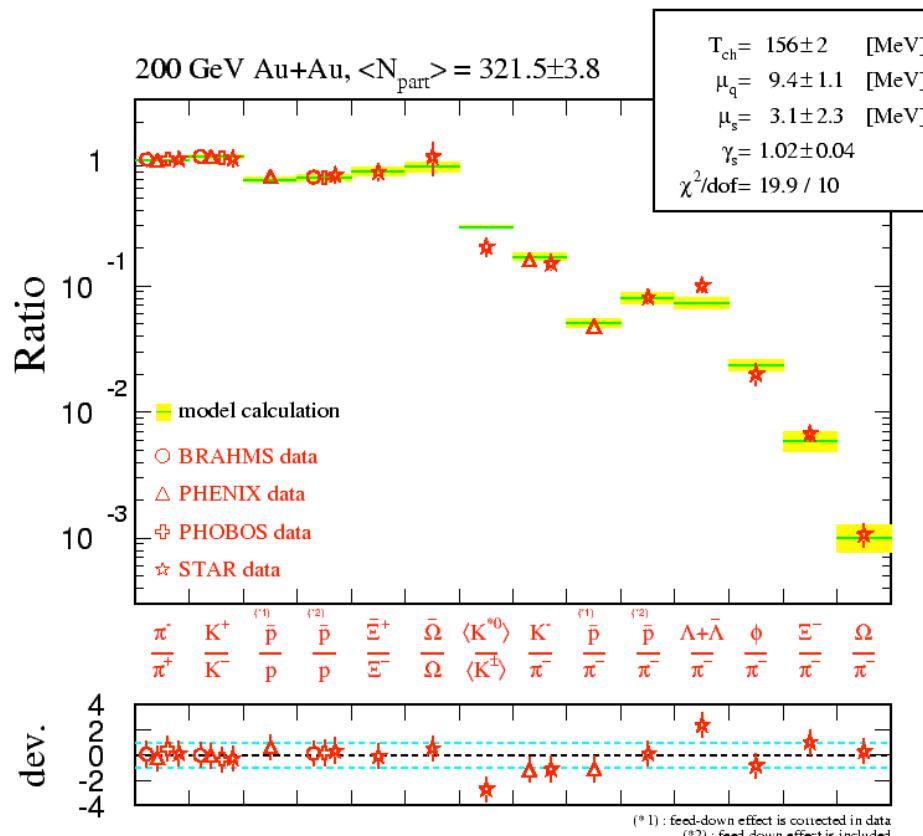
Hadron Spectra From RHIC

mid-rapidity, $p+p$ and $Au+Au$ collisions at 200 GeV





Hadron ratios and chemical fits



Au + Au at 200 GeV

(top 10% central collisions)

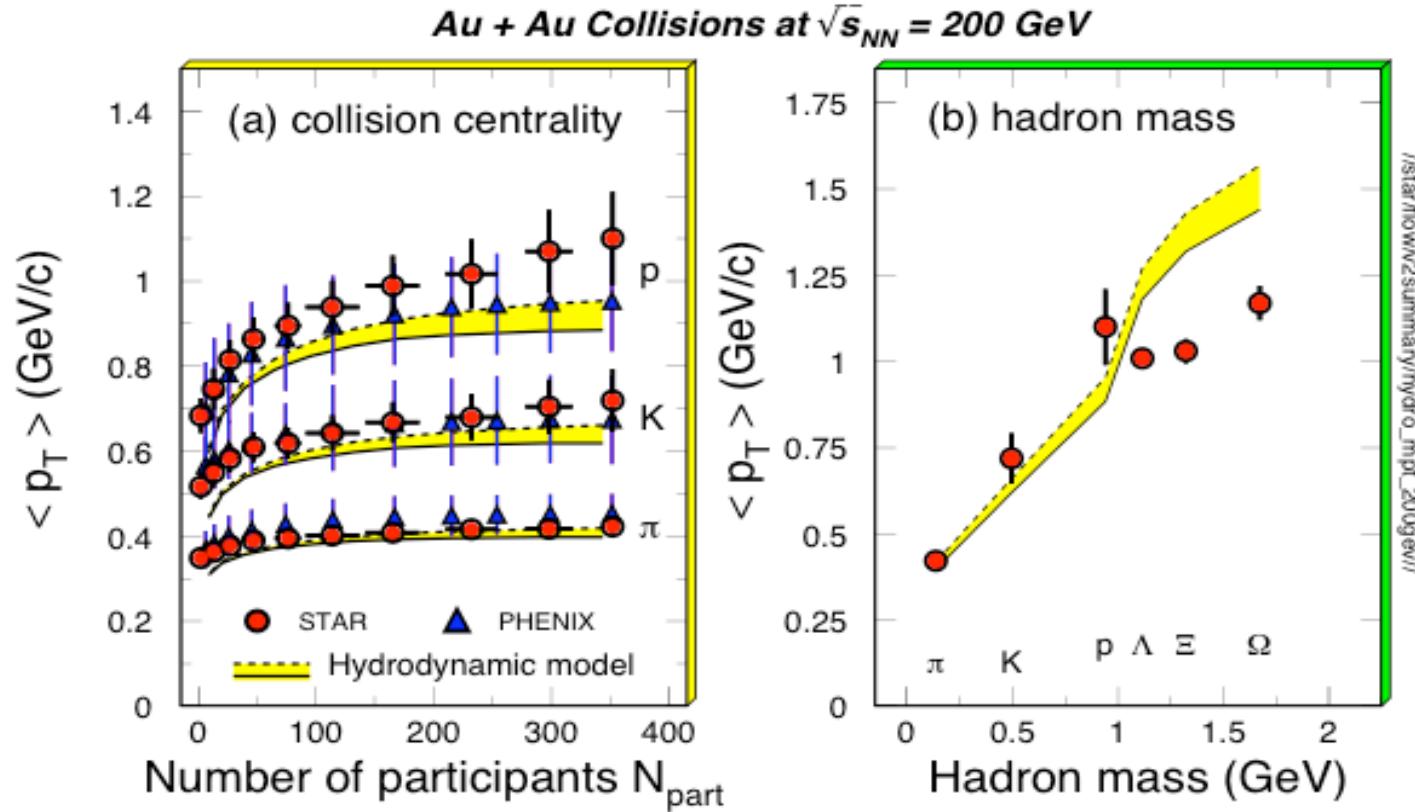
1) The model reproduce data within (almost) one sigma

2) Chemical freeze-out temperature

$$T_{\text{ch}} \sim 150-160 \text{ MeV}$$

3) Chemical fugacity \square_s is unity - chemical equilibrium between s-quark and light quarks. Only reached in central collisions at RHIC.

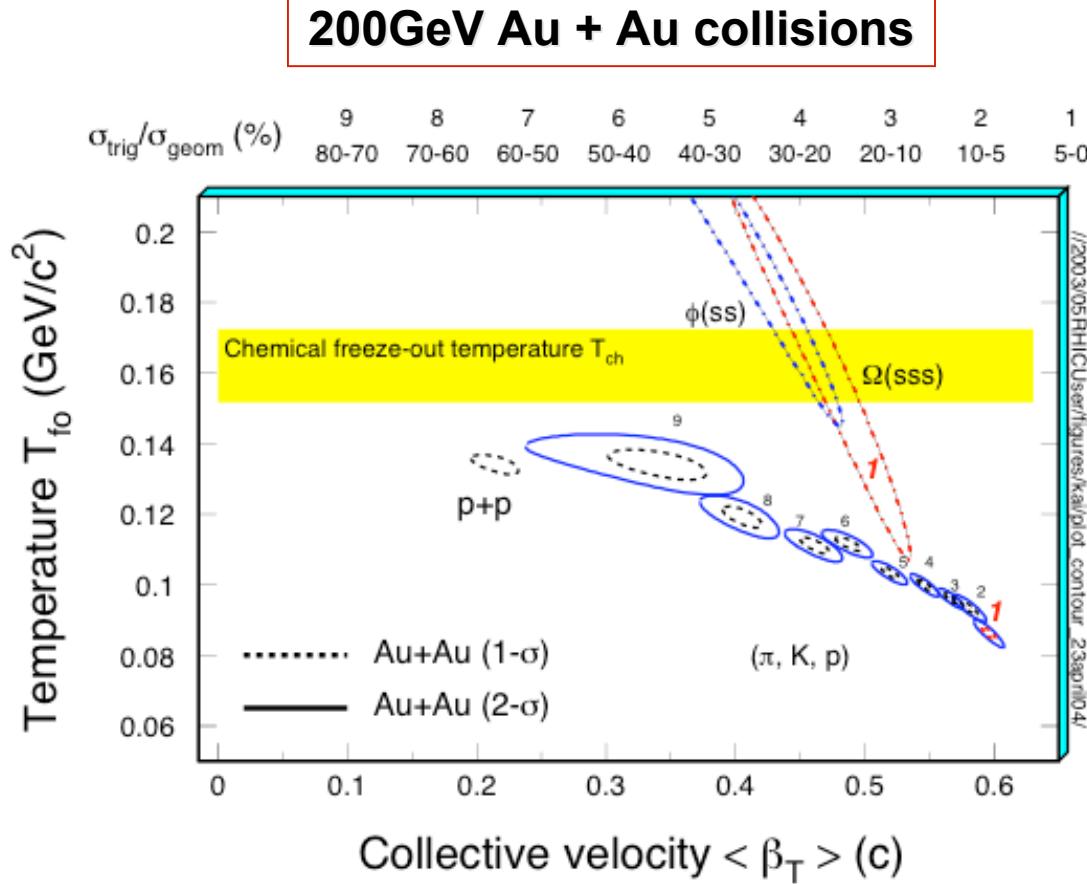
Compare with Model Results



Model results fit to π , K , p spectra well, but over predicted $\langle p_T \rangle$ for multi-strange hadrons - **Do they freeze-out earlier?**

Phys. Rev. C69 034909 (04); *Phys. Rev. Lett.* **92**, 112301(04); **92**, 182301(04); P. Kolb et al., *Phys. Rev. C67* 044903(03)

Thermal fits: T_{fo} vs. $\langle \bar{q} q \rangle$



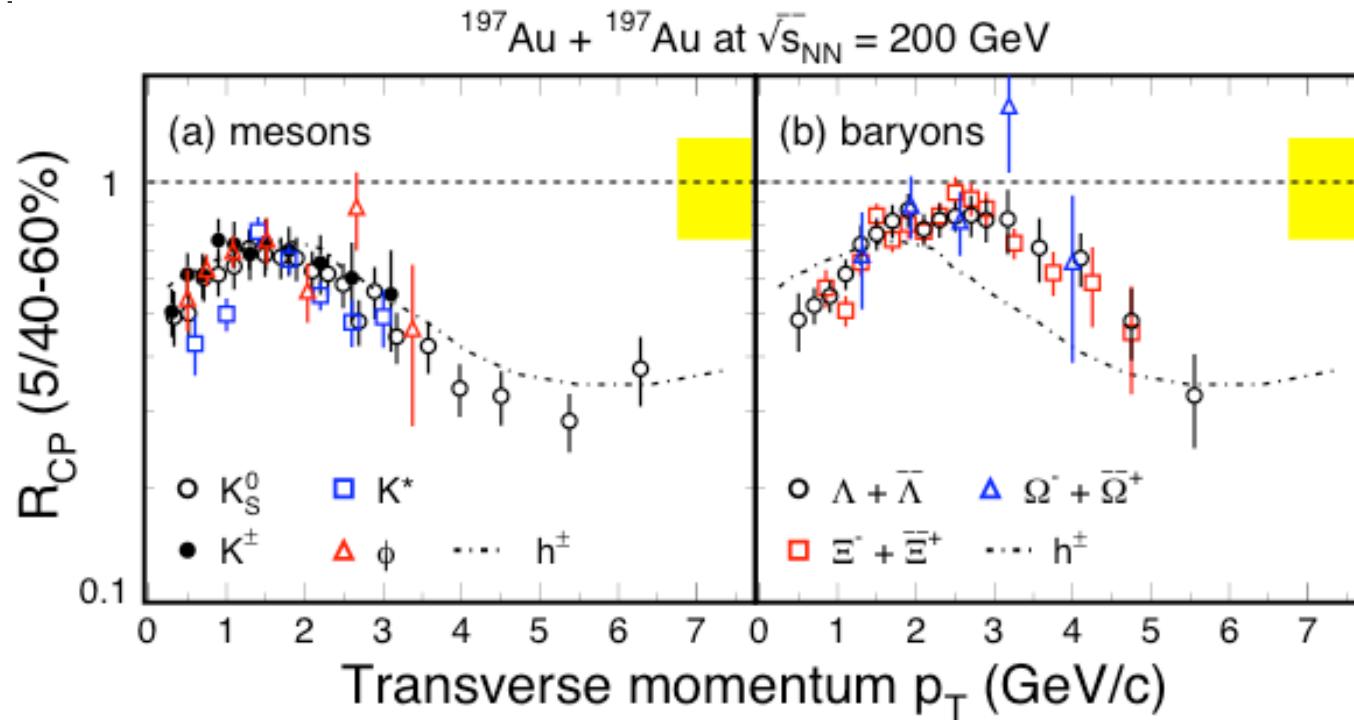
Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

- 1) $\bar{q} q$, K , and p change smoothly from peripheral to central collisions.
- 2) At the most central collisions, $\langle \bar{q} q \rangle$ reaches 0.6c.
- 3) Multi-strange particles Ω , $\bar{\Lambda}$ are found at higher T_{fo} ($T \sim T_{ch}$) and lower $\langle \bar{q} q \rangle$

⇒ Sensitive to early partonic stage!
 ⇒ How about v_2 ?

STAR: NPA715, 458c(03); PRL 92, 112301(04); 92, 182301(04).

Nuclear Modification Factor



$$R_{CP}(p_T) = \frac{d^2 N^{central}}{d^2 N^{peripheral}} / \left(\frac{N^{central}}{N^{peripheral}} dp_T dy \right)$$

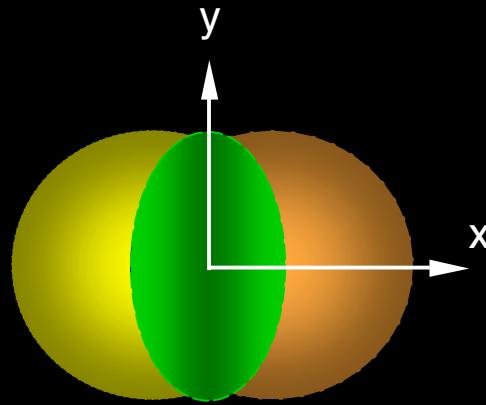
- 1) Baryon vs. meson effect!
- 2) Hadronization via coalescence
- 3) Parton thermalization (model)

- (K^0 , ϕ): *PRL* **92**, 052303(04); *NPA* **715**, 466c(03);
- *R. Fries et al, PRC* **68**, 044902(03)

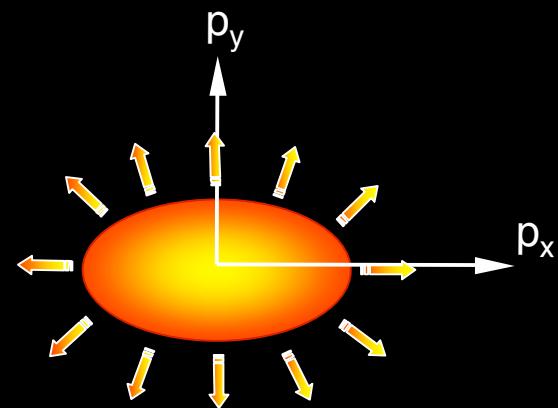


Anisotropy Parameter v_2

coordinate-space-anisotropy



momentum-space-anisotropy

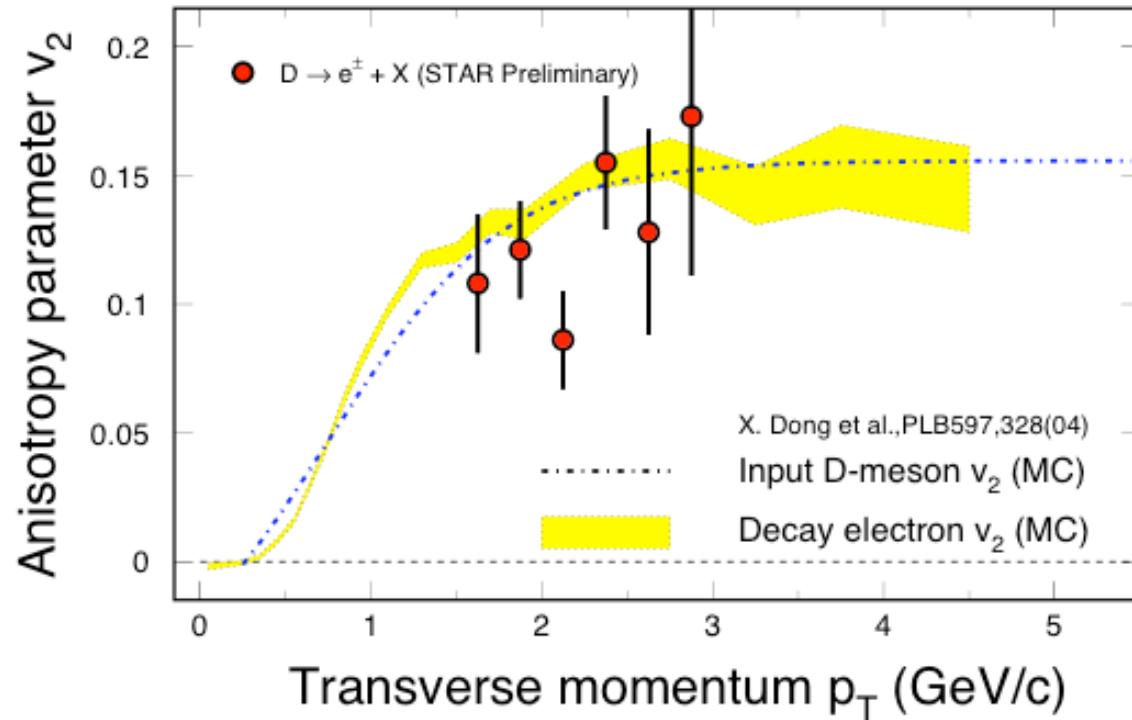


$$\square = \frac{y^2 - x^2}{y^2 + x^2}$$

$$v_2 = \langle \cos 2\square \rangle, \quad \square = \tan^{-1} \left(\frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

Open charm v_2 - a comparison

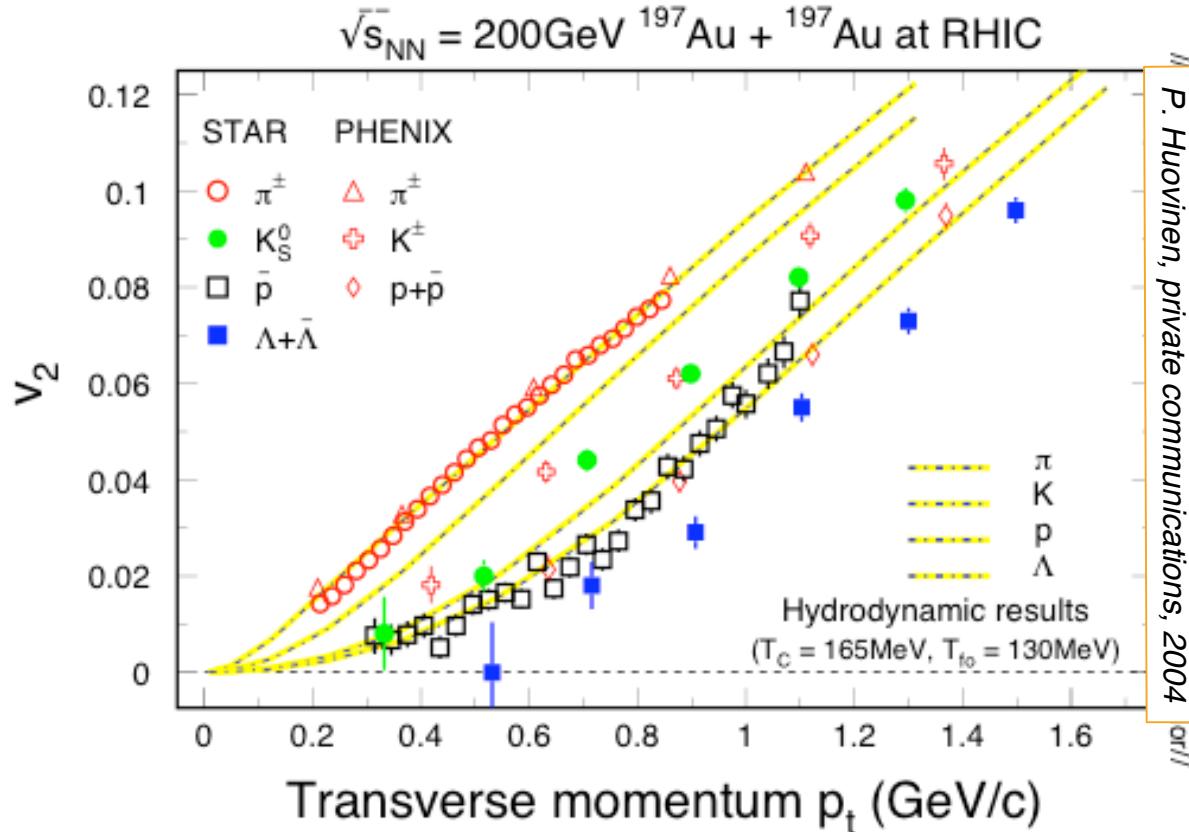


- 1) Constituent Quark Scaling for open charm hadron production?
- 2) Flow of charm-quark and the thermalization among light flavors?
- 3) ...????

Preliminary Data: F. Laue, SQM04

MC: X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, Phys. Lett. **B597**, 328(2004).

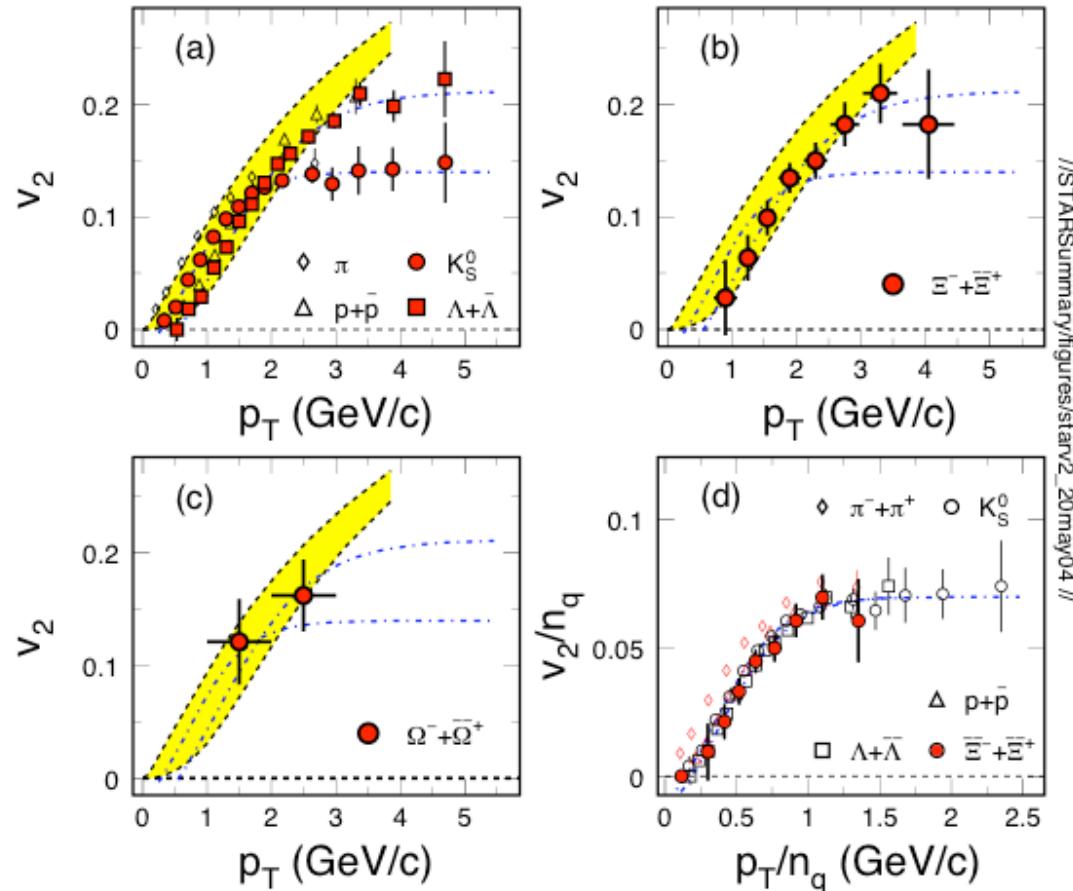
v_2 at low p_T region



- At low p_T , hydrodynamic model seem to fit for minimum bias events, especially the mass hierarchy.
- More theory work needed to understand details such as v_2 centrality dependence, consistency with hadron spectra.



v_2 at all p_T measured region



The v_2 , the spectra of multi-strange hadrons, and the scaling of the number of constituent quarks

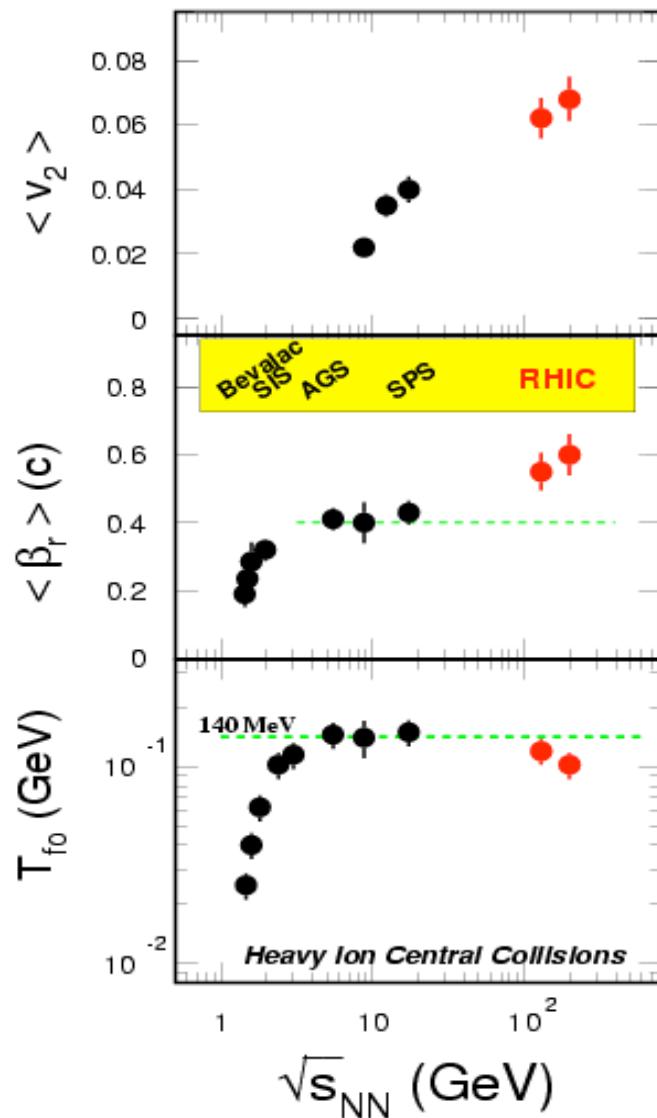
- ⇒ Partonic collectivity has been attained at RHIC!
- ⇒ Deconfinement, model dependently, has been attained at RHIC!

Next question is the thermalization of light flavors at RHIC:

- v_2 of charm hadrons
- J/ψ distributions !!

PHENIX: PRL91, 182301(03) **STAR**: PRL92, 052302(04)
Models: R. Fries et al, PRC68, 044902(03), Hwa, nucl-th/0406072

Bulk Freeze-out Systematics



The additional increase in $\langle v_2 \rangle$ is likely due to partonic pressure at RHIC.

- 1) v_2 self-quenching, hydrodynamic model works at low p_T
- 2) Multi-strange hadron freeze-out earlier, $T_{fo} \sim T_{ch}$
- 3) Multi-strange hadron show strong v_2



Summary & Outlook

- (1) Charged multiplicity - high initial density
 - (2) Parton energy loss - ***QCD*** at work
 - (3) Collectivity - pressure gradient ∂P_{QCD}
- ⇒ **Deconfinement and Partonic collectivity**

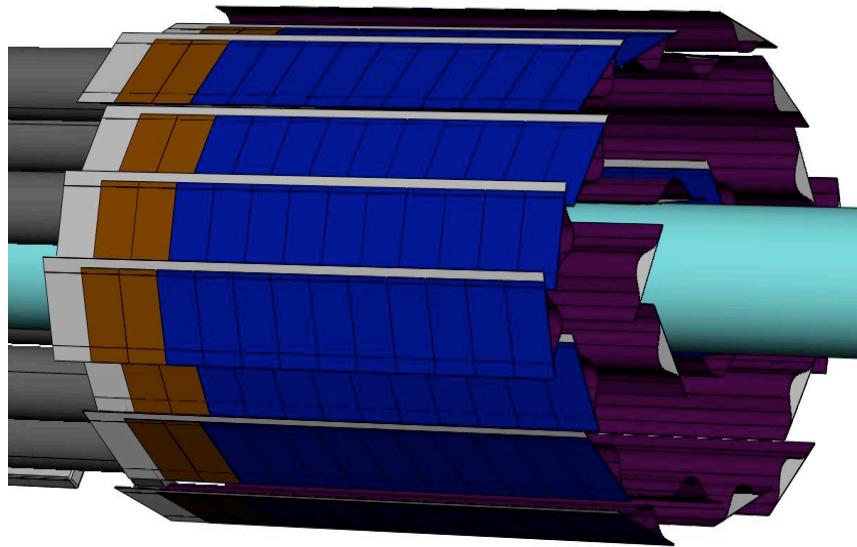
Open issues - partonic (***u,d,s***) thermalization

- heavy flavor v_2 and spectra
- di-lepton and thermal photon spectra



Upgrades at STAR

STAR MRPC - TOF



STAR MicroVertex Tracker

Active pixel sensors (APS)
Two layers of thin silicon

- Full open charm measurements
- Full resonance measurements with both hadron and lepton decays



Open Issues

1) Nuclear stopping/baryon transport:

- topological junction, a la Gyulassy
- nucleon structure function, a la Muller

2)* Thermalization and QGP temperature:

3)* Hadronization via coalescence/recombination:

- p+p collisions?
- low p_T pions? Where are gluons? Heavy flavor?

4) Chiral symmetry restoration:

Details for QGP discovery!

